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Gamma Rays from the Hg^{199}(n, γ)Hg^{200} Reaction and Energy Levels in Hg^{200}†

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γ-radiation from slow-neutron capture in Hg^{199} has been measured in the energy region from 150 to 8040 keV with a Ge(Li) spectrometer at the Brookhaven graphite reactor. The γ energies have been obtained with an accuracy varying between 0.10 keV for intense transitions and 3.0 keV for very weak transitions. γ radiation from resonance neutron capture has been measured between 5240 and 8040 keV. Altogether, 32 excited states in Hg^{200} are established, and their modes of decay are given. The lowest five levels have properties which are more complex than those predicted by the vibrational model. The neutron separation energy of Hg^{200} has been determined as 8028.8±0.5 keV. The neutron separation energy of Hg^{202} is 7755.1±1.5 keV.

I. INTRODUCTION

NUMEROUS experiments have been carried out in order to establish the nuclear level scheme[1] of Hg^{200}: The decay of Tl^{200} has been studied by several authors,[2–6] in greatest detail by Sakai, Ikegami, Yamazaki, and Saito.[7] Also, the decay of Au^{200} has been investigated.[2,8,9] Davis, Divatia, Lind, and Moffat[10] have performed Coulomb excitation experiments on Hg^{200} and thus have contributed valuable information about the first excited state of this nucleus. A great deal of information has become available through measurements of the γ-ray spectrum[11–16] and conversion electron spectrum[17,15] accompanying neutron capture in Hg^{199}. Studies of coincidences,[18–21] of angular correlations,[22–24] and of polarization correlations[25] of the neutron-capture γ rays have added to our knowledge about levels in Hg^{200} and their properties. Additional data have been obtained through resonance-capture experiments.[26–30]

As a result of these measurements, many levels with excitation energies up to 1500 keV have been well established and their spins and parities determined. Above 1570 keV numerous states have been found and spins and parities of several of these levels have been determined through very recent polarization correlation[31] and coincidence experiments.[32]

However, several questions concerning the depopulation of levels above 1570 keV, in particular of the level at 1570.3 keV, have not found a satisfactory answer. also, the energies of γ rays from capture of resonance neutrons have not yet been determined with sufficient accuracy to be useful in the construction of the level diagram.

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Therefore, emphasis has been placed in the present investigation on the determination of accurate transition energies and intensities from neutron capture in order to obtain a more consistent and complete scheme of the low-lying levels of Hg^{200}. For this purpose we have combined the data obtained during the present experiment, where mainly γ transitions above 1 MeV were measured with the Ge(Li) spectrometer with the previously reported detailed spectrum below 1 MeV.[16] The γ radiation from capture of predominantly thermal neutrons (Cd ratio $\sim$50) has been studied in this work between 150 and 8040 keV and the measurement of resonance-neutron capture γ radiation has been carried out in the γ-energy range from 5240 to 8040 keV. The interpretation of part of our results was facilitated considerably by the work of Groshev, Demidov, Ivanov, Lutsenko, and Pelekhov.[15]

II. EXPERIMENTAL METHODS AND RESULTS

A. Equipment

The measurement was carried out with 107-mg HgO with the following isotopic composition[33]: $<0.05\%$ Hg^{196}, 2.3% Hg^{198}, 83.45% Hg^{199}, 6.1% Hg^{200}, 2.36% Hg^{201}, 4.76% Hg^{202}, and 1.03% Hg^{204}. The capture cross sections of the isotopes other than Hg^{200} are so small compared with that of Hg^{199} (2400 b) that their contribution to the γ-ray spectrum is negligible for the indicated isotopic composition. The target material was enclosed in a thin aluminum container and irradiated in a neutron beam from the Brookhaven graphite reactor. The capture γ radiation was detected in a coaxial-type lithium-drifted germanium detector[34] roughly 9 cm^3 in volume. The Ge detector and the target were located in a lead shield used previously for external target coincidence experiments.[35] The pulses from the detector and/or a precision pulser[36] were fed to an FET-preamplifier[37] and were passed through a 200 ft long 93 Ω cable to an Ortec biased amplifier (Ortec Models 408, 410, 411) located in a thermally stabilized room. The pulses were stored in the 16 384 channel memory of a TMC pulse-height analyzer with a 1024-channel analog-digital converter (ADC, TMC-model 210B). Data were transferred onto magnetic tape with the help of a Datamec *D* 2020-unit. The data on the magnetic tape were analyzed by means of a CDC 6600 computer, using a program[38] which plots the spectra, fits Gaussian functions to the peaks, and lists their centroids, heights, and widths, and the respective errors.

B. Measuring Procedure

In the region between 30 and 700 keV the energies of γ transitions of Hg^{200} have been measured previously[16] with a curved crystal spectrometer with an accuracy better than that which can be achieved with our Ge-spectrometer. Between 700 and 1350 keV the quality of data which can be obtained with the Ge-spectrometer is comparable with that from the curved crystal spectrometer. Above 1100 keV the resolution and sensitivity of the Ge device are superior.

During test measurements gain drifts up to as much as 2 parts in 1000 were observed, even over periods of less than 1 h. A measurement of the dependence of the line width [full width at half-maximum] (FWHM) and line position on the counting rate when the counting rate was raised from 1000/sec to 4500/sec showed an increase of line width from 3.6 to 3.8 keV for the 368-keV transition in Hg^{200} and a decrease in peak position by as much as 4 parts in 1000. Consequently, it was not possible to obtain the energies of transitions in Hg^{200} by recording independently the Hg^{200} spectrum and the spectrum of energy reference sources, although both the amplification and the bias were kept constant. Therefore, the following method was applied during the measurements of the different energy regions of the Hg^{200} spectrum:

(1) Energies of γ transitions between 30 and 700 keV were measured only roughly and the emphasis was put on the determination of relative intensities [Fig. 1(a)].

(2) Between 700 and 1350 keV a run was made with the mercury target alone [Fig. 1(b)] and three runs were recorded in which the precisely known γ rays[39–41] from Co^{60} and Bi^{207} were measured simultaneously with the $Hg^{199}(n,\gamma)$ spectrum. The amplifier bias was varied from run to run. In addition, another measurement was performed in which a spectrum of equidistant pulser peaks with a spacing of 50 keV ranging from 850 to 1600 keV was superimposed on a spectrum of Hg^{200}, Co^{60}, and Bi^{207} lines. A potentiometer was used to normalize the pulser, so that the scale read directly in keV within the precision required for the determination of the energy differences of close lying peaks. The pulser used is specified to be linear to better than 1 part in 20 000.

(3) In the energy regions 1350–2200 keV [Fig. 1(c)] and 2200–3600 keV [Fig. 1(d)] where Na^{24} and Th^{228}

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[33] The material has been obtained from the Stable Isotopes Division, Oak Ridge, Tennessee.

[34] This detector has been prepared for us by Dr. H. Kraner at the Brookhaven National Laboratory Instrumentation Department. We are very much indebted to Dr. Kraner for his invaluable help and cooperation.

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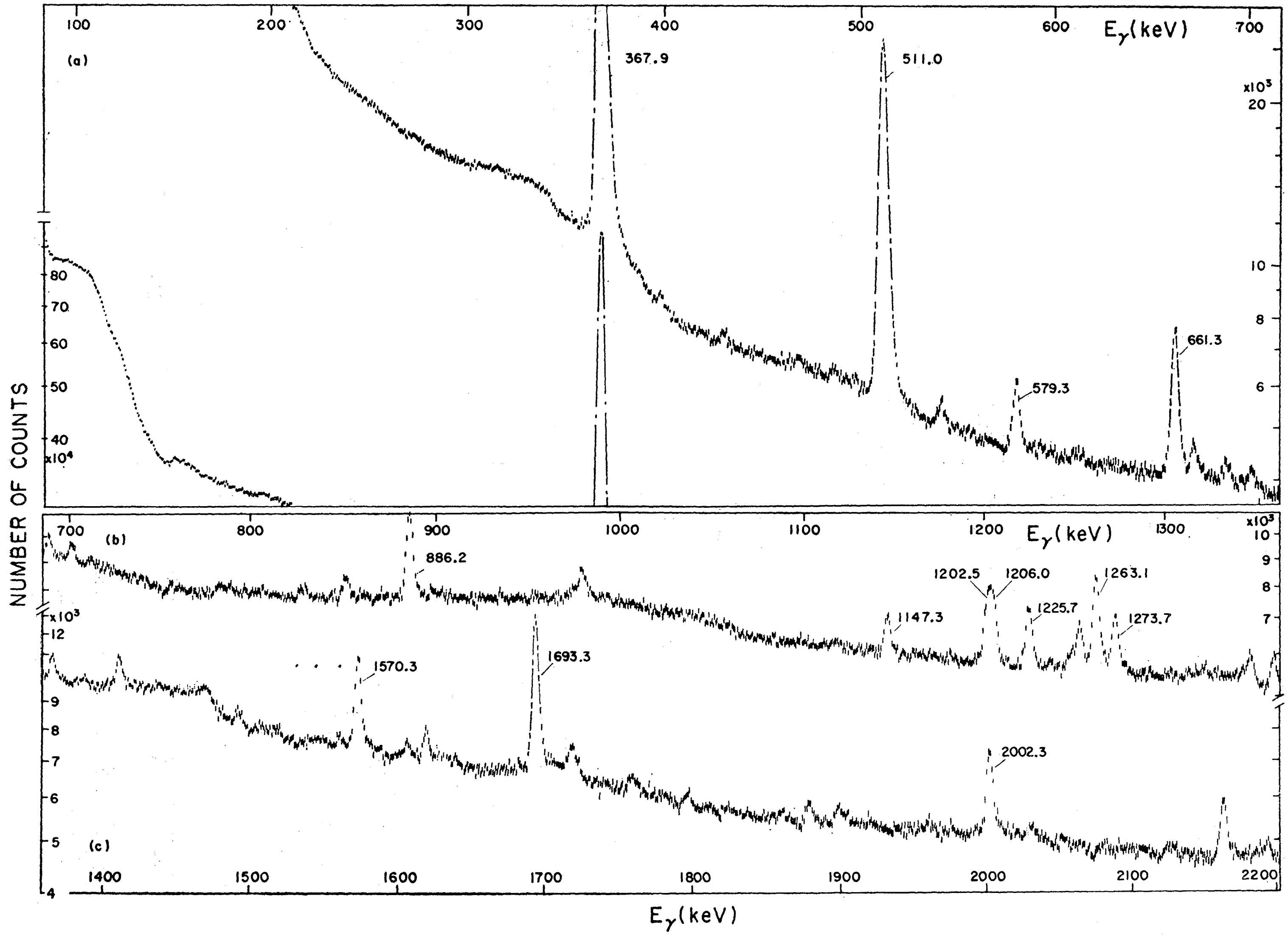

FIG. 1. γ-spectrum from slow neutron capture in HgO enriched in Hg^{199}, measured with a Ge(Li) spectrometer at the Brookhaven graphite reactor.

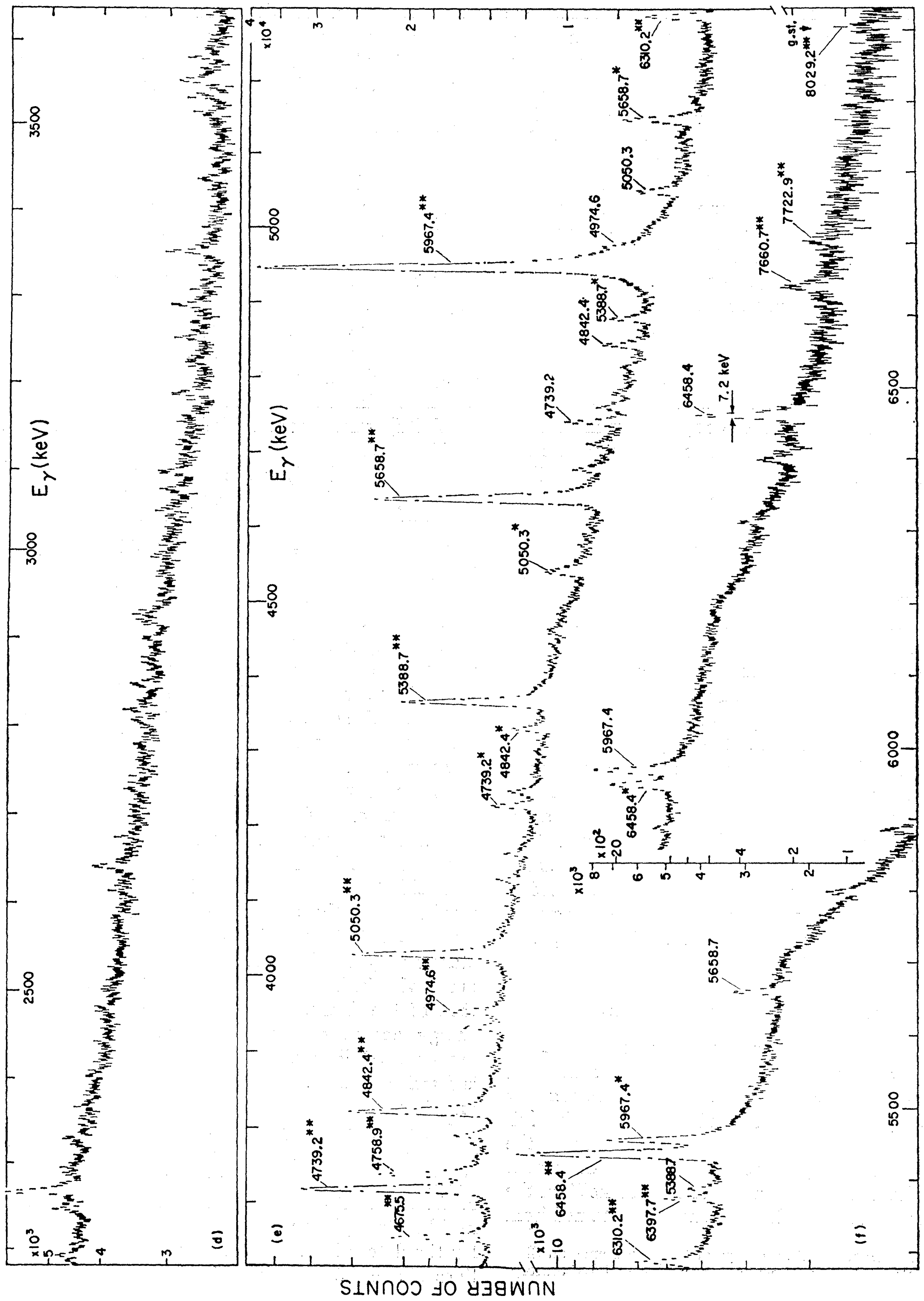

FIG. 1. (*continued*).

were used as reference sources,[39] a different procedure was applied because of the overlap of the Hg^{200} γ-ray spectrum and the reference lines. These spectra were recorded separately without changing the amplifier settings but each was measured "quasi-simultaneously" with a set of pulser peaks. For this purpose, several pulser spectra separated by approximately equal time intervals were superimposed on the reference ($Na^{24}+Th^{228}$) and Hg^{200} spectrum. Here the pulser peaks served as markers to link the Hg^{200} and reference spectra. We consider the quasi-simultaneous superposition of pulser peaks to be an effective method for reducing the influence on the data of drifts in the electronic equipment which was neither gain- nor bias-stabilized. In addition, a Hg^{200} spectrum was recorded without pulser and reference sources to find relatively weak lines [cf. Fig. 1(c)].

(4) The spectrum between 3600 and 5300 keV was measured in the same manner as in (3) above [Fig. 1(e)]. The neutron capture γ-ray spectrum from a melamine target was recorded in order to compare the energies of transitions in Hg^{200} with nitrogen line-energies which have been measured very accurately by Greenwood.[42]

(5) Similar measurements were made in the 5300–8100-keV region [Fig. 1(f)]. Sodium carbonate (Na_2CO_3) was taken as the reference target and the precisely known and intense 6395.1-keV Na line was used for energy calibration.[43]

In order to be able to identify weak lines as transitions in Hg^{200} a separate run was taken with an HgO target containing the natural isotopic mixture. The measuring time for these runs amounted to 4 days.

In addition, the γ-ray spectrum from the capture of epi-cadmium neutrons was recorded in the energy range from 5240 to 8040 keV after inserting a sheet (0.5 mm) of cadmium into the neutron beam. The spectrum from the small (107 mg) target containing HgO enriched in Hg^{199} was measured during a period of 30 h. In order to identify lines from other mercury isotopes, a short run (4 h) was made with a target of about 2 g of natural HgO.

C. Evaluation of the Data and Results

γ-ray energies were determined from the calibration lines in the various energy regions. At higher energies, the single- and double-escape peaks of both the mercury and reference lines were utilized as well as the full energy peaks. The energy differences of most of the peaks in the pulse-height spectrum were obtained with the use of the well-known energy of 511.006 keV[44] of the annihilation radiation. While the energies obtained from the nitrogen reference lines agreed with those found with the sodium calibration line, the centroid of the latter line was determined with much better accuracy during a given time so that the nitrogen data were only used as an additional check. The relative γ-ray intensities were evaluated on the basis of a detector efficiency-curve obtained previously.[45]

The energies of the lines observed during the resonance-neutron-capture experiments were determined, with the help of the pulser, by normalizing to the energies determined from slow neutron capture. Several resonances contribute to the intensity of each of the γ-ray lines. For this reason the γ-ray intensities from resonance neutron capture are not particularly meaningful and hence will not be given.

The spectra recorded during the capture of neutrons without the cadmium filter are shown in Fig. 1, and the γ-ray energies and relative intensities with their errors are listed in Table I. The experimental line-width (FWHM) varied from 3.6 keV at 370 keV to 7.2 keV at 6500 keV.

Figure 1(b) clearly shows that the "1204-keV line" is complex, probably a doublet, the decomposition of which provides the basis for an answer to the question about the depopulation of the 1570.3-keV level (see Sec. III B).

In the region from 1500 to 4600 keV, more γ transitions were observed by Groshev *et al.*[15] than in this experiment, owing to the low efficiency of the Ge(Li) spectrometer in this energy region. Above 4600 keV all transitions observed by Groshev *et al.*[15] have been seen except for three very weak lines, two of which were reported as questionable. While these authors used natural mercury as a target, and therefore could not unambiguously assign weak transitons ($I_\gamma \lesssim 0.5\%$) to the isotope Hg^{200}, such an assignment has become possible in the present experiment. Our data indicate the presence of a weak 6431 keV transition which they would not have been able to resolve from the 6458-keV line. Thus, the sensitivity of the spectrometer used in this work is comparable to that of the excellent Compton spectrometer used by Groshev and co-workers. The resolution of our device is, however, about a factor 2.5 better than that of the Compton spectrometer[15] and the present energy accuracy exceeds that achieved in previous experiments[15,32] by about an order of magnitude, which is decisive for the application of the energy-combination principle.

Gamma-ray energies above 4600 keV were determined in a two-step measurement: (1) The energy of the strong 6458-keV line in Hg^{200} was compared with that of the (6395.1 ± 0.4) keV[43] γ ray in Na^{24}. (2) The 6458-keV line in Hg^{200} was then used as secondary reference for the determination of the energies of the remaining lines above 4.6 MeV in Hg^{200}. The total energy error

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TABLE I. γ energies and relative γ intensities and their errors for the stronger transitions in Hg^{200} from neutron capture.

	E_γ (keV)	dE_γ (keV)	Δ/dE_γ	I_γ rel	dI_γ/I_γ (%)		E_γ (keV)	dE_γ (keV)	Δ/dE_γ	I_γ rel	dI_γ/I_γ (%)		E_γ[a] (keV)	ϵ_2[b] (keV)	Δ/ϵ_2	I_γ rel	dI_γ/I_γ (%)
c	367.97	0.02	0.10	70	10	d	2259.7	1.0	0.02	0.9	50		4675.52	0.50	0.20	1.8	15
	398.20	0.40	0.15	0.42	20	e	2272.00	0.50	0.16	1.6	40		4739.22	0.40	0.92	4.3	15
d	420.0	~	...	0.23	40	d, e	2296	~	...	0.9	~		4758.92	0.40	0.10	2.1	15
	430.20	0.40	0.59	0.39	20		2639.80	0.40	0.20	2.9	15		4799.7	1.2	0.11	0.11	25
d	467.0	~	...	0.17	30		2819.00	0.50	1.22	0.8	30		4811.77	0.50	0.80	0.5	20
	485.80	0.50		0.37	30		2901.80	0.40	0.05	1.1	20		4842.44	0.35	0.00	2.9	15
	540.80	0.30	0.50	0.86	20		2921.3	0.6	0.18	1.0	20		4954.17	0.50	0.40	0.55	20
	579.40	0.20	0.09	2.10	10	d	2984.6	~		0.4	40		4974.67	0.45	0.20	0.8	15
c	661.39	0.07	1.28	6.0	10	d	3050	~		0.6	~		5050.32	0.40	0.43	3.3	15
	688.95	0.25	0.01	0.66	20	d	3073	~	...	0.6	~	d	5134.7	1.0	(~0)	0.10	~
	701.58	0.15	0.10	0.56	15		3185.9	0.5	0.90	2.4	15		5150.14	0.50	0.30	0.21	25
	828.43	0.30	0.44	0.50	20		3216.0	0.8	0.72	0.7	25		5388.74	0.35	0.31	2.7	15
	851.42	0.25		0.85	20		3269.0	1.0	0.78	0.7	20	e	5568.4	~	...	0.16	~
c	886.27	0.10	0.10	3.7	10		3288.2	1.0	0.95	2.6	20		5658.74	0.40	0.58	4.4	15
d	898.7	0.7	0.12	0.32	25	d, e	3311	~		0.4	~		5731.92	0.50	~0	0.17	25
	1147.33	0.20	0.50	1.70	10		3352.8	1.5	0.22	0.6	15		5800.8	1.5	0.40	0.09	25
	1202.55	~0.20	0.61	3.5	20		3500.2	1.0		0.4	25		5967.47	0.20	0.45	10.2	15
	1206.00	~0.20	0.57	3.5	20	d	3633.4	1.0		0.3	35		6310.27	0.30	0.18	0.41	20
	1225.73	0.10	1.36	2.9	10		3750.3	1.0		0.3	30		6397.74	0.20	0.20	0.41	15
	1254.18	0.20	0.24	1.7	15	d	3828.3	1.0		0.3	~	d	6431.6	3.0	1.18	0.14	~
	1263.15	0.10	0.93	4.3	10	d, e	3841.0	1.0		0.2	~		6458.42	...	...	3.2	15
	1273.70	0.15	0.81	2.5	10		3869.1	1.5		0.4	25		7660.74	0.40	0.10	0.04	20
	1349.46	0.30		1.3	20	d	3952.3	1.5		0.22	35	f	7722.9	1.5	...		...
	1363.06	0.25	0.06	1.5	20	d	4018.4	1.5		0.16	40		8029.2	1.5	0.36	0.015	30
d	1384.9	~	...	0.35	40	d, e	4072	~		0.14	~		8029.6	1.0	0.94	Energies from the capture of resonance neutrons	
	1407.80	0.15	0.30	2.2	15	d, e	4095	~		0.2	~	g	7754.9	1.5	...		
d	1515	~	...	0.7	30		4119.3	1.0		0.38	20	d	7660.5	1.5	0.20		
	1558.02	0.25	0.48	0.65	25		4176.1	2.0		0.27	30	h	6457.92	0.30	1.33		
	1570.33	0.20	0.33	6.8	10	d, e	4245.6	2.0		0.17	30		6435.7	0.7	0.77		
	1604.65	0.30		0.8	25		4273.2	1.0		0.33	20		6396.9	0.8	1.00		
d, e	1630.1	2.0	0.46	0.6	~	e	4373	~		0.6	20		6310.9	0.7	0.86		
	1693.30	0.30	0.64	14.0	10		4458.8	1.5		0.22	20		5967.2	0.4	0.20		
	1718.15	0.40	0.62	2.1	20		4537.8	1.5		0.23	20		5658.6	0.6	0.10		
d	1757.98	0.30		1.0	40		4555.5	1.5		0.20	25		5388.6	1.0	0.25		
	2002.28	0.25	0.20	6.4	10		4575.4	1.0		0.6	25						

[a] These energies are obtained using a value of 6395.1 keV[43] for the γ line from neutron capture in sodium as standard.
[b] The errors ϵ_2 include only the fitting errors and errors introduced by the electronic equipment. They do neither include the energy error (0.4 keV) of the standard nor our calibration error ϵ_1 ($=0.20$ keV) (see text).
[c] Lines used for energy calibration. The energies E_γ and the energy errors dE_γ are taken from Maier *et al.* (Ref. 16).
[d] Very weak lines, the existence of which is not uniquely established in the present experiment.
[e] Complex groups or lines which have been observed close to stronger peaks in the pulse-height spectrum.
[f] Aluminum impurity line.
[g] Ground-state transition in Hg^{202}.
[h] It is possible that the peak observed during resonance neutron capture contains transitions to both the 1570.4- and the 1573.8-keV states. Then the value $\Delta/\epsilon_2=1.33$ does not apply.

dE_γ of these transitions includes the error (0.4 keV) of the sodium standard, the calibration error ϵ_1 and the error ϵ_2 resulting from the measurement outlined under (2):

$$dE_\gamma=(0.4+\epsilon_1^2+\epsilon_2^2)^{1/2}. \tag{1}$$

In total, five comparisons were made with the sodium line. The resulting values for the energy differences D_i between the strong sodium γ-ray line (6395.1 keV) and the intense 6458-keV γ-ray line in Hg^{200} are given in Table II together with the combined errors δD_i in the determination of the positions of the γ-ray peaks by the computer program.

There are two principal sources of error in the comparison of the 6395-keV sodium line and the 6458-keV line of Hg^{200}: (1) peak fitting errors, and (2) local nonlinearities in the electronic system. Since the computer program attempts to fit a Gaussian function to peaks which are actually somewhat asymmetric, the errors δD_i in the peak centroid positions are considerably overstated by a factor which depends on the ratio between the peak height and the statistical error of the number of counts. This is seen from the internal consistency of the values for D_i listed in Table II. When the relations for the computation of the mean value $\bar{D}$ and its error $\delta\bar{D}$ as given by Kohlrausch[46] are applied

$$\bar{D}=\sum_i g_iD_i/\sum_i g_i, \tag{2}$$

$$\delta\bar{D}=[\sum_i g_i(\bar{D}-D_i)^2/(n-1)\sum_i g_i]^{1/2}. \tag{3}$$

TABLE II. Energy difference between the 6395-keV γ line in Na^{24} and the 6458-keV γ line in Hg^{200}.

$E(6458)-E(6395)$ D_i (keV)	Combined fitting error δD_i (keV)
63.67	0.50
63.32	0.50
63.18	0.45
63.18	1.10
63.20	0.40
Mean value: 63.32±0.20 keV	

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[46] F. Kohlrausch, *Praktische Physik* (B. G. Teubner Verlag, Leipzig, 1950), Vol. I.

$\bar{D}=63.31$ keV and $\delta\bar{D}=0.09$ keV when the weights g_i have been set equal to the inverse of the squares of δD_i.

If the effect of local nonlinearities is assumed to be much larger than the fitting errors, and the calculation is performed with equal weights, then

$$\bar{D}=63.32 \text{ keV} \quad \text{and} \quad \delta\bar{D}=0.05 \text{ keV}.$$

The two values for $\bar{D}$ agree well and the values for $\delta\bar{D}$ are much smaller than the individual fitting errors δD_i. For if the external error of $\bar{D}$ is calculated

$$\delta\bar{D}=1/[\sum(1/\delta D_i)^2]^{1/2}, \tag{4}$$

then

$$\delta\bar{D}=0.23 \text{ keV}.$$

In view of the fact that the internal error is very small (about 1/100 of the linewidth), the possibility of small additional systematic errors cannot be discounted. We therefore consider

$$\epsilon_1=0.20 \text{ keV}$$

to be the best estimate for the calibration error.

Our absolute energies listed in Table I are in very good agreement with the γ energies given by Bartholomew *et al.*[32] The energy values given by Groshev *et al.*,[15] including the neutron separation energy, are systematically about 6.3 keV too low. Apart from this, the consistency of the data of Groshev and co-workers is much better than one would expect when considering the quoted errors, i.e., if one increases their energies by 6.3 keV, their numbers agree with ours within a small fraction of their errors. The energies of the γ transitions observed during the capture of resonance neutrons are also listed in Table I. In the experiment carried out by Groshev and co-workers[15] a weak transition to the ground state of Hg^{200} was observed. This line is seen also in the present experiment. As Groshev *et al.* have pointed out, a resonance-neutron capture experiment would help to decide whether this line is due to capture of epithermal neutrons only or if the compound state is partially 1^-. We have performed this experiment and found that $(60\pm20)\%$ of the 8028 keV-γ intensity observed during the capture of unfiltered neutrons is due to capture of neutrons with energies below the cadmium cutoff. The numerical value given above depends, of course, on the energy distribution of neutron spectrum.

Since the weak 6435-keV transition is, relative to the 6458 transition, stronger in the resonance-neutron capture spectrum than in the thermal spectrum [Fig. 1(f)], a more precise energy for this line is obtained from the resonance-neutron capture data. The two values obtained are 6435.7±0.7 and 6431±3.0 keV, respectively. The expected energy for the primary transition leading into the 1593.56-keV level is 6435.16 keV. The 6435-keV line was not observed in previous resonance-neutron capture experiments on Hg^{199} targets because of insufficient resolution. In the resonance-neutron capture in the natural mercury oxide target, a (7754.9±1.5)-keV line was observed which is very much reduced in intensity in the run with the Hg^{199} target. From this and the Hg^{202} neutron binding energy (7760±6 keV) as given by Mattauch, Thiele, and Wapstra,[47] we conclude that this line constitutes the ground state transition in Hg^{202}. Thus, the neutron separation energy of Hg^{202} is (7755.1±1.5) keV.

III. LEVEL SCHEME

For the construction of the level diagram of Hg^{200} (Fig. 2) use has been made of all information obtained in previous experiments whenever these results were consistent with our data. From the neutron separation energy 8026.7±3.8 keV as given by Mattauch *et al.*[47] it is evident that the 8029.3±1.5 keV transition proceeds from the compound state to the ground state. With this latter and more precise neutron-separation energy, a group of new levels is postulated on the basis of the reasonable assumption[27] that the high-energy transitions above 4.6 MeV originate from the compound system. Additional states are disclosed through the energy combination principle and the transition energies as determined above 1 MeV in this experiment and for $E_\gamma<1$ MeV by Maier *et al.*[16]

A. Levels below 1.5 MeV

The level sheme includes excited states at 368, 947, 1029, and 1254 keV, each of which has been observed and discussed in considerable detail in several previous papers, in particular by Groshev *et al.*,[15] Sakai *et al.*,[7] Maier *et al.*,[16] and Bartholomew *et al.*[32] Sakai *et al.*[7] have found a K-conversion line which they have interpreted as belonging to a transition (1028.7 keV) de-exciting the 1029 keV level. However, no γ ray with an energy of 1029 keV has been observed by us. A comparison of their conversion electron intensities with our upper limit for the ratio of the intensities of the 1029- and 661-keV lines is incompatible with the assumption that the 1029-keV transition is $E2$. If it were $M1$, a γ ray of about 1.5 times our detection limit should have been observed and for this reason we consider $M1$ as not a very probable assignment. The present data support the conclusion arrived at by Maier *et al.*[16] that this 1029-keV transition is $E0$, which implies 0^+ spin and parity for the 1029-keV level.

B. Levels between 1.5 and 2.0 MeV

The de-excitation mode of the 1.57-MeV level populated in the Tl^{200} decay is different from that of the 1.57-MeV state populated by the (n,γ) reaction. Although this implies that a close lying doublet of levels exists at 1.57 MeV as has also been pointed out by Groshev *et al.*, it has not been possible in previous (n,γ)

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[47] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).

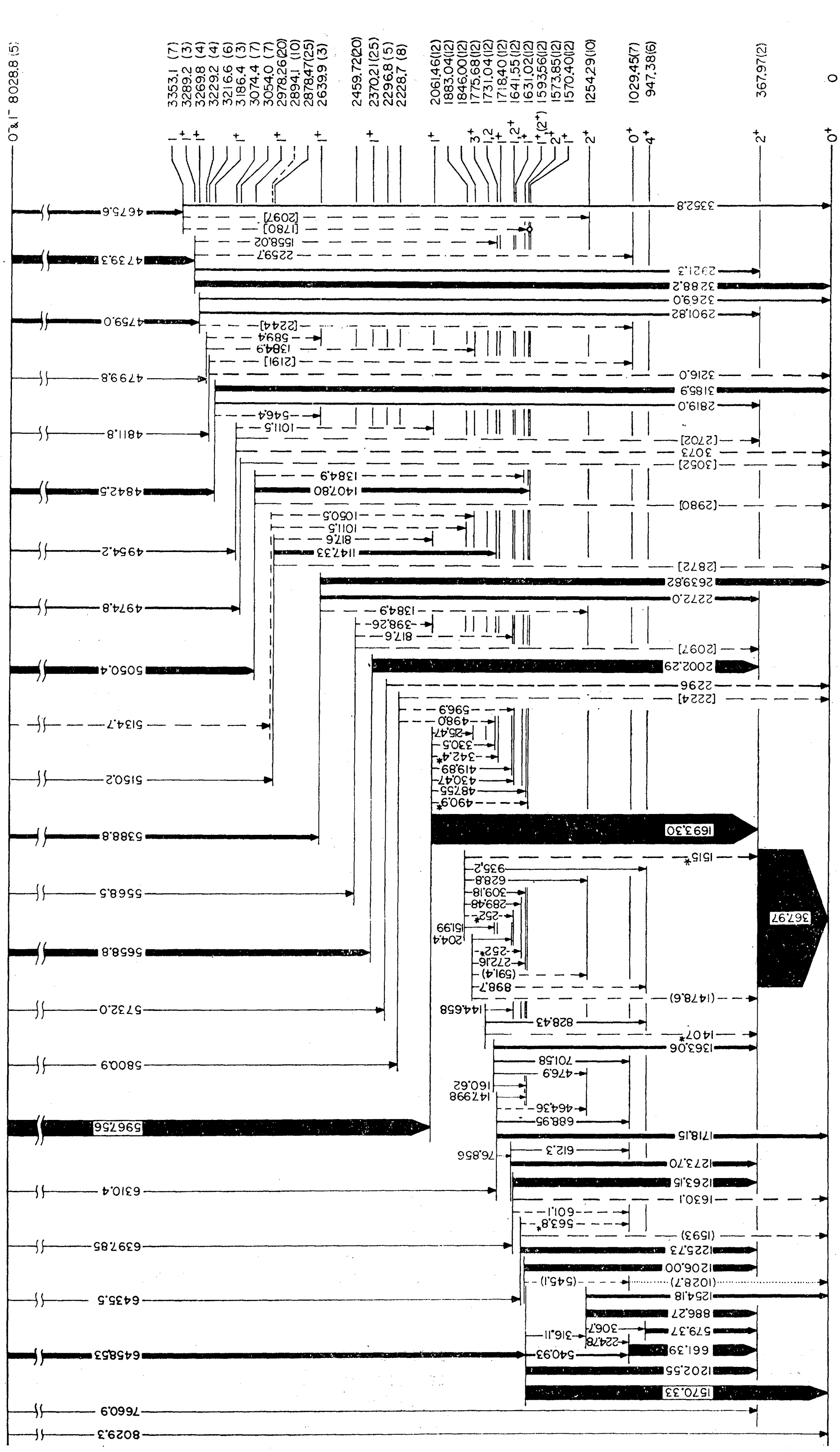

FIG. 2. Proposed nuclear level scheme of Hg²⁰⁰. Transitions drawn as a solid line have been observed either during the present experiment or by Maier *et al.* (Ref. 16). Their location in the diagram is unambiguous for levels with energies below 1640 keV and either definite or very probable for higher-lying states. The dotted 1028.7-keV transition has been observed only by Sakai *et al.* (Ref. 7) as a *K*-conversion line. Energies taken from these authors are given in round brackets and energies from Groshev and coauthors in square brackets. Transitions which have not been observed in this experiment or by Maier *et al.* are shown as dashed lines. Also, transitions the assignment of which is not well established or which are located several times in the scheme are drawn as dashed lines. Complex lines are indicated by an asterisk. The width of the lines is approximately proportional to the γ intensity of the transitions for $I_\gamma \gtrsim 0.3/100$ *n*. The excitation energies of the levels are given in keV. The numbers in parentheses give the uncertainty in units of the last digit.

experiments to determine with sufficient accuracy the energies and intensities of the transitions from this proposed doublet of states to the 368-keV level because of insufficient resolution and energy accuracy. Groshev *et al.*[15] correctly assigned the 1570-keV transition as leading to the ground state and mentioned that a "1204"-keV line might populate the 368-keV level. They considered 40% of the total intensity of the "1204"- and "1207"-keV lines (which they saw as a single peak) as an upper limit for the "1204"-keV line intensity. The high symmetry seen at the broad peak which is centered around 1204 keV in our spectrum [Fig. 1(b)] shows that the intensity of the lower-energy line (1202.5 keV) is close to 50% of the intensity sum of both lines (1202.5 and 1206.0 keV).

Bartholomew *et al.*[32] have shown in their coincidence work that a level at about 1569 keV (see Fig. 11 of Ref. 32) is de-excited via a 1.569- and a 1.20-MeV transition and have assigned this level 1^+ spin and parity in agreement with the result of Groshev *et al.*[15] Maier *et al.*[16] established the state under discussion through an accurate energy combination. They showed that the level is depopulated through a 540.9-keV transition and the weak 316.1-keV transition, which had been observed only in their experiment. Their resolution and energy accuracy, however, was not sufficient above 1200 keV to arrive at a complete description of the decay of this level. Segel *et al.*[29] found the 1.57-MeV level to decay through a 1.57- and a 1.20-MeV line and found tentative evidence for a 0.55-MeV transition to the 1029-keV level. The transitions with energies of 6458.53, 1570.33, 1202.55, and 540.80 keV form loops which close very well within the fairly small energy errors as determined in the present experiment. On the basis of the 1^+ assignment[15,25,32] of the 1570-keV level, all transitions which are expected to have reasonable intensities have been identified, including the very weak 316-keV line given by Maier *et al.*[16]

The 1573.8-keV level was first seen by Herrlander *et al.*[3] during the investigation of the Tl^{200} decay. A detailed proposal for the decay of this level has been made by Sakai *et al.* who suggest, in addition to the intense 1206.8-keV line to the level at 368 keV, a ground-state transition (1569 keV), and a 545.1-keV line leading to the 1029-keV level. This latter assignment does not contradict the energy difference of the levels as given in our scheme. The γ intensity of the 545.1-keV transition is probably below the limit of sensitivity of the device used by Maier *et al.* We therefore include the transition tentatively in our level diagram. The assignment of the 1569-keV line by Sakai *et al.* is probably correct. We cannot isolate this line (which, according to our more precise energies, should have an energy of 1573.8 keV) from the very intense 1570.3-keV transition. There exists, however, another possibility: the 1569-keV line might be identical with our 1570.3-keV transition which would imply that the 1570.3-keV state is very weakly populated in the decay of Tl^{200}. In that case the 1202.5-keV transition should be present, but very weak, in the spectrum from the decay of Tl^{200}, where however the tail of the much more intense 1206-keV transition would inhibit the observation of the 1202-keV radiation. Therefore, the problem of the detailed deexcitation of the 1573-keV state has not yet been solved unambiguously. A careful determination of the energy of the "1569"-keV line in the Tl^{200} decay seems to be the easiest method. The work of Sakai *et al.* strongly supports a 2^+ character for this state.

The level at 1593 keV has been disclosed in decay scheme spectroscopy.[3,7–9] Our data are in agreement with these results, but only the 1225-keV transition is intense enough to be seen with the Ge(Li) spectrometer. The ground-state transition has been tentatively included in our decay scheme. The 1593-keV level seems to be populated also through a very weak 6432-keV primary transition in thermal neutron capture. The resonance neutron-capture spectrum clearly shows a γ line with an energy of 6436 keV which enables us to establish the 1593-keV state independently of any of the previous information on this level. Our data require $I=1$, (2) for this level. Even parity is inferred from the data of Groshev *et al.*; Sakai *et al.* have assigned it 1^+ spin and parity.

Groshev *et al.*[15] have proposed a level at 1632 keV to which they assign (1^+). Bartholomew *et al.*[25] have confirmed this assignment. The state is not populated with appreciable intensity in the Tl^{200} decay and its deexcitation occurs almost exclusively through the 1263-keV transition (see Fig. 2). A 1630-keV γ line is seen as a very weak peak [see Fig. 1(c)]. Its intensity is less than that given by Groshev *et al.*

The 1641-keV state is reported by Sakai *et al.* and by Maier *et al.*, and the results arrived at in the present work are in agreement with these authors. We do not have strong enough evidence for a 388.1-keV transition between this state and the 1254-keV level. The decay of the 1641-keV level is best understood on the basis of a $1^\pm$ or 2^+ assignment.

Groshev *et al.* have inferred a (1^+) state at 1720 keV from the observation of a primary γ transition and the $M1$ multipolarity of the 1720-keV line. A detailed proposal for the de-excitation of this level has been presented by Maier *et al.*[16] Our data confirm their results.

Herrlander *et al.*[3] and Sakai *et al.* have proposed a level at an excitation energy of 1733 keV. Maier *et al.* have studied the decay of this state in detail and their results are largely confirmed in the present work. The depopulation of the level implies spin 1 or 2.

A level at 1776 keV has been established through the Tl^{200} decay studies[3,7] and it is also populated after neutron capture.[15,16,32] The data of Sakai *et al.* determine the spin and parity of the level as 3^+, which is consistent with our results. It is interesting to note that the branching ratio $I_\gamma(1409)/I_\gamma(828)$ as determined by Sakai *et al.*

is much smaller than the ratio of the γ intensities observed in neutron capture. This implies that the 1407-keV line seen in the neutron-capture reaction is complex and that its main component must be located somewhere else in the level scheme.

The state at 1846 keV has only been given by Sakai *et al.*[7] Their results agree for the most part with our data.

Herrlander *et al.*[3] and Sakai *et al.*[7] have proposed a level at 1883 keV. The information obtained by us concerning the de-excitation of this state, as shown in the level diagram (Fig. 2), is in agreement with their results and those obtained in previous (n,γ) experiments.[15,16]

C. Further Levels

A group of 15 levels with excitation energies above 2060 keV are disclosed through the observation of primary γ transitions feeding these states, none of which has been observed through decay-scheme spectroscopy. Ten of these levels have been obtained in earlier (n,γ) experiments by Groshev *et al.*[15] The 2060-keV state has also been reported by Maier *et al.*[16] Carlos *et al.*[21] have observed levels at 2.37 and 2.64 MeV through coincidence measurements. Bartholomew *et al.*[32] have studied a total of 11 states above 2060 keV and have determined the spins of most of these levels to be 1^+.[23,25] The present data confirm essentially all of these previous results. Several new states are shown in the level diagram and their modes of decay are indicated.

As mentioned before, we have constructed the level diagram by making use of all information available. This procedure is unambiguous as long as the accuracy of the data is adequate; this is the case when levels are fed through primary (n,γ) transitions or when states are interconnected through intense transitions. Almost all transitions above 4600 keV and below 3360 keV seen in this experiment are included in the scheme. One cannot expect to locate all lines since some of them may proceed to or from states which are populated weakly so that their assignment cannot be obtained with a sufficiently high degree of confidence. The level diagram includes numerous low energy lines ($E_\gamma < 1$ MeV) which have been given by Maier *et al.*[16]; also, several transitions measured by Groshev *et al.*[15] and Sakai *et al.*[7] have been incorporated.

Since the total number of levels in the scheme is quite high (33), the chance for low-energy lines to fit by accident between these states is sizeable. For this reason, we have not attempted to search for additional levels using the energy combination principle to a larger extent than has already been done. It should also be emphasized that the location of several lines in the diagram is uncertain. The 1384.9-keV transition is a striking example. It fits into the scheme in three different places. This is of course due to the fact that the energy of this transition has not been determined precisely (Table I). The consistency of the level diagram can be checked by comparing energy differences $E_i - E_k$ between levels i and k with transition energies $E_\gamma + R$ (where R is the recoil energy). Since the level energies are obtained from the transition energies, one will expect that the ratios Δ/dE_γ and Δ/ϵ_2 with $\Delta = |E_i - E_k - E_\gamma - R|$ are less than 1 in 32 cases (number of excited states) plus 68% of the remaining cases where a value for Δ/dE_γ for $E_\gamma < 4.5$ MeV or Δ/ϵ_2 for $E_\gamma > 4.6$ MeV has been given in the respective columns in Table I. It is found that $\Delta/dE_\gamma \leq 1$ and $\Delta/\epsilon_2 \leq 1$ occurs in 80% of these cases, which lends support to the level diagram. Apart from complex lines, 37 low energy lines given by Maier *et al.*[16] have been included in our scheme. For this set, $\Delta/dE_\gamma \leq 1.0$ has been found in 81% of the cases. The neutron separation energy S_n has been determined from the mean of individual numbers $S_{ni} = E_{\gamma i} + R_i + E_i$, where $E_{\gamma i}$ is the energy of the primary transition leading to the level i, R_i is the recoil energy loss, and E_i is the excitation energy of the level i as obtained from the transition energies of the lines de-exciting the state i. For this purpose only those 14 levels, the decay of which has been sufficiently well established, have been used. From Eqs. (2) and (3) a value $[8028.83 \pm (0.4^2 + \epsilon_1^2 + 0.05^2)^{1/2}]$ keV has been found. Since the error contributions 0.4 keV, ϵ_1, and 0.05 keV are uncorrelated, the total error of the neutron binding energy S_n is, with $\epsilon_1 = 0.20$ keV: $dS_n(\text{keV}) = (0.4^2 + 0.20 + 0.05)^{1/2} = 0.45$ keV, and we have therefore $S_n = 8028.8 \pm 0.5$ keV.

IV. DISCUSSION

The energies, spins, and parities of the first four excited states in Hg^{200} suggest that this isotope can be considered as a vibrational nucleus.[48] However, the ratio of the excitation energies of the second and the first excited states is 2.57, which is considerably larger than the predicted value 2.00 and well above the average experimental value 2.2 observed for other vibrational nuclei.[48] Furthermore, the branching ratio of the transitions leading from the second 2^+ level $(2^{+\prime})$ to the ground state and to the first 2^+ state is 0.46 which is incompatible with a pure two-phonon character for this level since a transition directly to the ground state should be forbidden. Actually it has been found[49] that this transition does occur in other vibrational nuclei, but its intensity is very small in comparison with that of the $2^{+\prime} \to 2^+$ transition.

Because the spins and parities do not forbid $M1$ admixture into the $2^{+\prime} \to 2^+$ transition, the knowledge of the mixing ratio

$$\delta^2 = \frac{I_\gamma(E2, 2^{+\prime} \to 2^+)}{I_\gamma(M1, 2^{+\prime} \to 2^+)}$$

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[48] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

[49] See the compilation by O. Nathan and S. G. Nilsson in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), p. 636 ff.

is of particular interest, since Kraushaar and Goldhaber[50] have shown that the crossover branching ratio $I_\gamma(2^{+\prime}\rightarrow 0^+)/I_\gamma(2^{+\prime}\rightarrow 2^+)$ is small in cases where the $M1$ admixture into the $2^{+\prime}\rightarrow 2^+$ transition is small; furthermore, there is some evidence that a large crossover branching ratio is frequently related to a considerable $M1$ admixture into the transition from the second to the first excited 2^+ state. The pure phonon model implies the absence of an $M1$ admixture and the magnitude of such a component would therefore indicate the extent to which the wave functions of the levels involved deviate from pure phonon configurations. The experimental evidence in Hg^{200} is contradictory: The $2^{+\prime}\rightarrow 2^+$ transition has been reported as "$E2(+M1?)$" (Ref. 15) and "$M1+E2$, δ small." (Ref. 7) Unfortunately these results do not define the $M1$ admixture within narrow limits.

Recently, Bhatt[51] has suggested that the first 2^+ and 4^+ states in the even mercury isotopes are largely due to the excitation of protons, with the neutrons remaining in the unexcited configuration, and that the second 2^+ state ($2^{+\prime}$) is predominantly a neutron excited state with the protons remaining unexcited. Although Bhatt succeeds in explaining the low-lying states in the odd A indium isotopes on the basis of this model, it is necessary, for the case of Hg^{200}, to require considerable admixture of other configurations into the wave functions proposed by Bhatt. Otherwise the $2^{+\prime}\rightarrow 2^+$ transition would be a two-step transition which would not be observable in competition with the one-step $2^{+\prime}\rightarrow 0^+$ transition because of its extremely small relative transition probability. A similar difficulty would arise for the interpretation of the 306.7-keV transition between the $2^{+\prime}$ and 4^+ levels. This transition and a 224.7-keV γ ray from the second 2^+ state to the second 0^+ level have been assigned by Maier *et al.*[16]

These transitions, which can be understood neither on the basis of a pure phonon model nor on the basis of Bhatt's proposal, have been predicted by Brink, De Toledo Piza, and Kerman,[52] who have treated anharmonic effects up to and including quartic terms. They have related the reduced $E2$-transition probabilities to the quadrupole moment Q of the first excited state:

$$B(E2,\, 2^{+\prime}\rightarrow 0^{+\prime}) = 2.8e^2Q^2\,, \tag{5}$$

and

$$B(E2,\, 2^{+\prime}\rightarrow 4^{+}) = 2.06e^2Q^2\,, \tag{6}$$

where $0^{+\prime}$ stands for the second 0^+ state. Using the γ intensities as given by Maier *et al.*, one obtains

$$B(E2,\, 2^{+\prime}\rightarrow 0^{+\prime})/B(E2,\, 2^{+\prime}\rightarrow 4^{+}) = 2.7\pm 0.8\,,$$

to be compared with the predicted value 1.36. In view of the approximate nature of the model, the difference between these numbers would not appear to be significant. It should be noted that the existence of the $2^{+\prime}\rightarrow 4^+$ and $2^{+\prime}\rightarrow 0^{+\prime}$ transitions requires, in the framework of the model of Brink *et al.*, the existence of a nonzero static quadrupole moment for the first excited state in Hg^{200}. Brink *et al.* also present formulas which permit the calculation of the excitation energies of three-phonon levels. The $I^\pi = 6^+$ state of this quintet of states is expected at ~1.7 MeV, but its spin is so high that the level would not be populated to an appreciable degree by the (n,γ) reaction. The other members are predicted around 2.0 MeV (2^+), 2.12 MeV (4^+), 2.4 MeV (3^+), and 2.7 MeV (0^+). No definite conclusions about these levels can be drawn from our results.

The $M1$ character of the 1570-keV ground state transition[15] also implies multipolarity $M1$ for the 540-keV transition. The results of Sakai *et al.*[7] and Groshev *et al.*[15] strongly suggest $M1$ character for the 1202-keV transition as well. Assuming that the 316-keV transition is also $M1$, we find for the relative $B(M1)$ values: $B(M1,\, 1570) : B(M1,\, 1202) : B(M1,\, 540) : B(M1,\, 316) = 1{:}00{:}1.15{:}3.1{:}1.6$, which implies that the transitions are about equally fast. The de-excitation of the state at 1573.8 keV can be understood quite easily on the basis of its spin 2 and the character of the 1206-keV transition, which is given as "$E2+M1$, small δ" by Sakai and coworkers.[7] Neglecting the $E2$ contribution, the only modes of decay would be the $M1$ transition to the 368-keV level and a low-energy (319.5-keV) $M1$ transition to the level at 1254 keV. The latter transition seems to have a $B(M1)$ value considerably smaller than that of the 1206-keV line.

We would like to draw attention to the fact that several states, particularly the levels at 2061 and 2370 keV, decay strongly to the first excited state, while no transitions to the two-phonon triplet are seen. This is especially interesting since there are also many low-energy lines which de-excite the 2061-keV state.

Evidently both more detailed experimental results and a more sophisticated theoretical treatment are a prerequisite to an understanding of the excited levels in Hg^{200}.

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[50] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).

[51] K. H. Bhatt, Phys. Letters **24B**, 22 (1967).

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