Gamma-Ray Decay in Hg^{200}†

R. E. SEGEL*
Aeronautical Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio
(Received May 28, 1958)

$\gamma-\gamma$ cascades following thermal neutron capture in Hg^{109} have been measured. A three-crystal pair spectrometer was used to measure the high-energy gamma rays and a single NaI(Tl) crystal spectrometer detected the lower energy radiation. A detailed comparison is made between the experiment reported here, the previously known high-resolution mercury capture gamma-ray spectrum, and the previously measured decay scheme of Tl^{200}. Several discrepancies between the capture gamma ray and β-decay work are resolved, though others remain. By combining the results of the three experiments, probable spin and parity assignments are made for several of the low-lying levels in Hg^{200}. With these spin assignments, some conclusions are drawn as to the relative transition probabilities for the various multipolarity radiations present.

INTRODUCTION

THE spectra of the gamma rays following thermal neutron capture have recently been the subject of considerable investigation. This work has, in general, concentrated on obtaining the singles spectra of the emitted gamma rays under as high a resolution as possible. From the energies and intensities of the gamma rays present, it is possible to infer many of the features of the decay scheme. However, the spectra are, in general, so complex that even with measurements at an energy resolution of approximately 1% for the gamma rays, it is usually impossible to deduce an unambiguous decay scheme. For this reason, a program has been initiated by the Aeronautical Research Laboratory group at Brookhaven to study the $\gamma-\gamma$ cascades following thermal neutron capture.

EXPERIMENTAL TECHNIQUE

The low yield inherent in high-resolution β-ray spectrometers or crystal diffraction spectrometers renders them impractical to use for coincidence measurements with the neutron fluxes available, and it is, therefore, necessary to use sodium iodide for the γ-ray detectors in spite of the relatively poor resolution obtained. Sodium iodide, however, has the further disadvantage of yielding a rather complex spectrum for incident monoenergetic gamma rays. This effect is particularly severe at γ-ray energies of several Mev where pair production is the dominant mode for electron production and, therefore, the full energy peak is accompanied by two lower energy peaks corresponding to the escape of one or both of the 0.511-Mev annihilation quanta. While crystals large enough (~10-in. linear dimensions) to act as total absorption counters up to an energy to several Mev appear to be commercially available, no crystal of this size with sufficiently good γ-ray resolution has been brought to this author's attention. Since a thermal neutron is generally captured into a state of excitation energy of from 6 to 9 Mev, it is necessary to separate gamma rays in this energy region.

In order to circumvent the above difficulty, a three-crystal pair spectrometer was constructed. The spec-

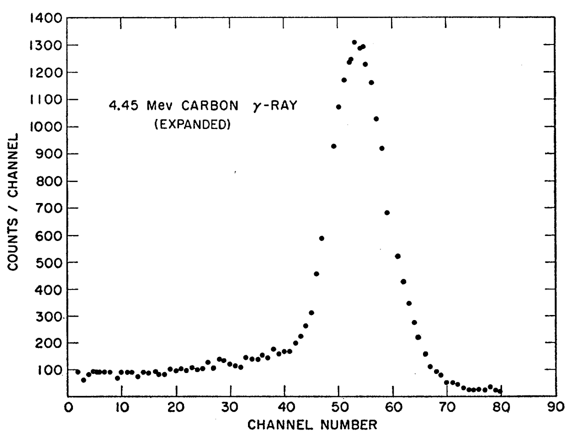


FIG. 1. Three-crystal pair spectrometer response to 4.45-Mev carbon gamma ray. The scale is expanded such that channel 0 corresponds to channel 200 on an absolute scale.

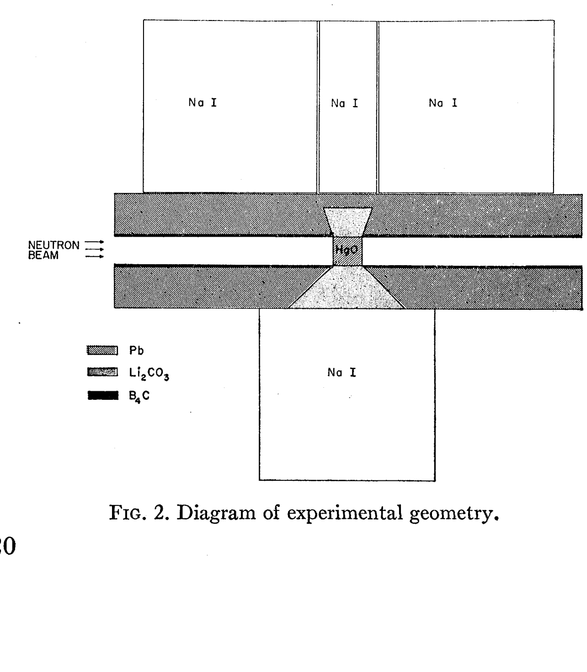


FIG. 2. Diagram of experimental geometry.

† Work performed at Brookhaven National Laboratory under the auspices of the U. S. Atomic Energy Commission.
* Guest scientist at Brookhaven National Laboratory, Upton, New York.

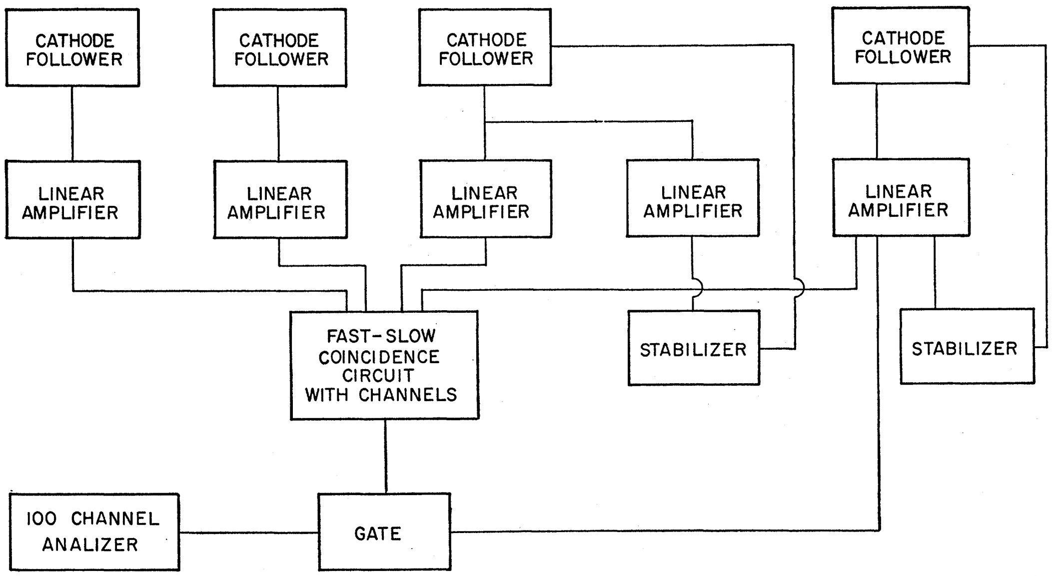


FIG. 3. Block diagram of electronics.

trometer consisted of a 3-in. thick, 1-in. diameter center crystal and two 3-in. thick, 3-in. diameter side crystals. The three counters are placed in coincidence, with the side counters channeled on 0.511 Mev. The coincident spectrum in the center crystal for the 4.43-Mev gamma ray from a Po-Be source is shown in Fig. 1. The low-energy tail is due to bremsstrahlung and electron escape. The spectrometer has an approximately constant γ-ray resolution of about 4% from 4 to 8 Mev (remembering that the pulse height in the crystal corresponds to $E_\gamma - 1.02$ Mev).

The lower-energy gamma rays (up to $\sim$3 Mev) were detected with a 3-in. diameter, 3-in. thick NaI(Tl) crystal.

The target was placed in a thermal neutron beam emerging from the BNL research reactor. A schematic of the experimental geometry is shown in Fig. 2. The detectors were placed close (1 in.) to the target in order to increase the solid angle, and, therefore, the coincidence yield. The beam hole was lined with boron carbide in order to prevent neutrons from boiling through the lead shield, and Li^6 was interposed between the target and the detectors in order to absorb scattered neutrons. A $\frac{3}{16}$-in. lead filter between the target and the pair spectrometer served to lower the singles rate in the spectrometer crystals, and also to reduce crystal-to-crystal coincidences between the center crystal of the pair spectrometer and the low-energy γ-ray counter.

A block diagram of the electronics is shown in Fig. 3. Double delay-line clipped amplifiers were used in order to minimize spectral distortion due to pulse pileup, as singles rates of up to 10^5 pulses/sec were present. The photomultiplier tubes of the center crystal in the pair spectrometer and the low-energy counter were stabilized using stabilizers of the de Waard[1] type. A strong line in the singles spectrum was used as the stabilization reference for the low-energy counter, while a Cs^{137} source was placed near the center crystal to serve as a reference for the high-energy counter. A separate amplifier was used to feed the high-energy counter stabilizer. This extra amplifier was necessary as the amplifier gain for the center crystal was set at about 100 kev/volt and, therefore, the Cs^{137} peak fell at too low a voltage to permit adequate stabilization.

The fast-slow coincidence circuit had a resolving time of 10^{-7} sec. Rather wide channels ($\sim$200 kev) were used on the side crystals of the pair spectrometer. The pair-spectrometer spectrum appeared to be the same in the pulse-height region corresponding to gamma rays of energy greater than 4 Mev as when narrower channels (50 kev) were used on the side crystals.

In the interaction of thermal neutrons with nuclei, the only process which can compete with elastic scattering is neutron capture followed by γ emission, except at the extrema of the periodic table where occasionally heavy charged particle emission is possible. The probability for γ-ray emission is a sharply increasing function of γ-ray energy ($\Gamma_\gamma \sim E^3$ for dipole radiation, E^5 for quadrupole, etc.) and, therefore, the capturing state will primarily emit high-energy gamma rays in the region of about 5–8 Mev. Except for transitions to the ground state or to isomeric states, each high-energy gamma ray will be promptly followed by one or more lower-energy gamma rays. The running procedure was, therefore, to channel on a high-energy line in the pair

[1] H. de Waard, Nucleonics **13**, No. 7, 36 (1955).

TABLE I. Gamma rays observed by Adyasevich, Groshev, and Demidov.[a]

γ-ray energy[b] (Mev)	Intensity (photons/100 captures)	Energy of level fed (Mev)
7.66±0.03	0.1	0.40±0.03
(7.08±0.05)	0.03	0.98±
6.95±0.05	0.03	1.11±0.05
6.44±0.03	4.5	1.62±0.03
6.31±0.05	2.4	1.74±0.05
5.99±0.03	10	2.07±0.03
(5.88±0.05)	2	2.18±
5.67±0.03	6.7	2.39±0.03
5.44±0.03	4.5	2.62±0.03
(5.28±0.05)	1.4	2.78±
5.05±0.03	6	3.01±0.03
4.94±0.05	3	3.11±0.05
4.82±0.03	10	3.24±0.03
4.69±0.05	6	3.37±0.05
(4.59±0.05)	3.5	
4.12±0.05	1	
3.80±0.05	1	
3.60±0.05	0.5	
3.50±0.05	0.5	
3.25±0.03	3	
3.14±0.03	3	
2.89±0.03	1	
2.64±0.03	3	
2.40±0.03		
2.29±0.03	4	
2.10±0.03		
2.02±0.015	6	
1.85±0.02		
1.73±0.01	13	
(1.62±0.02)		
1.59±0.02	4	
(1.49±0.02)		
1.41±0.02		
1.29±0.01	7	
1.22±0.015	6	
1.10±0.02	2	
1.01±0.02	3	
0.90±0.03	7	
0.83±0.02	2	
0.68±0.015	6	
0.58±0.02	3	
0.37±0.01	20	

[a] See reference 2.
[b] Energy values which have not been determined very precisely are given in parentheses.

spectrometer, and observe the coincident radiation in the low-energy counter with the aid of a 100-channel analyzer. The fourfold coincident yield was about one count per minute per 1% cascade for a totally absorbing target.

PREVIOUS WORK ON Hg^{200}

The capture γ-ray spectrum in mercury has been investigated by Adyasevich, Groshev, and Demidov[2] (hereafter referred to as A.G.D.). These workers used a Compton recoil spectrometer and found 42 lines in the energy region 0.37–7.66 Mev (throughout this paper all energies will be given in Mev). Over 90% of the thermal neutrons captured by natural mercury are captured by Hg^{199}, with no other isotope contributing more than 2% of the captures, and therefore all of the lines which have an intensity greater than 2 photons/100 captures can be presumed to be due to transitions in Hg^{200}. Nuclear mass measurements[3] yield a neutron binding energy in Hg^{200} of 8.06 Mev which is in agreement with the present work and the work of A.G.D.

Table I gives the lines measured by A.G.D. as well as the energies of the low-lying levels that the high-energy gamma rays feed. The 7.66, 7.08, and 6.95 lines are too weak to be assigned to Hg^{200} with certainty. However, the present work demonstrates that these lines are also due to Hg^{200}.

The decay scheme of Tl^{200}, which decays primarily by K capture to Hg^{200}, has been investigated by Herrlander and Gerholm[4] (hereafter referred to as H.G.) and their decay scheme is shown in Fig. 4. The levels at 0.37, 0.95, 1.59, and 1.73 Mev correspond to levels deduced from the capture γ-ray spectrum. Transitions to the other levels in the region between 1.57 and 1.89 Mev could have been missed in the capture γ-ray spectrum because of inadequate resolution. In the region where the measurements overlap, the only levels indicated from the capture γ-ray spectrum that are not seen in the β-decay work are the levels at about 1.10 and 2.07 Mev.

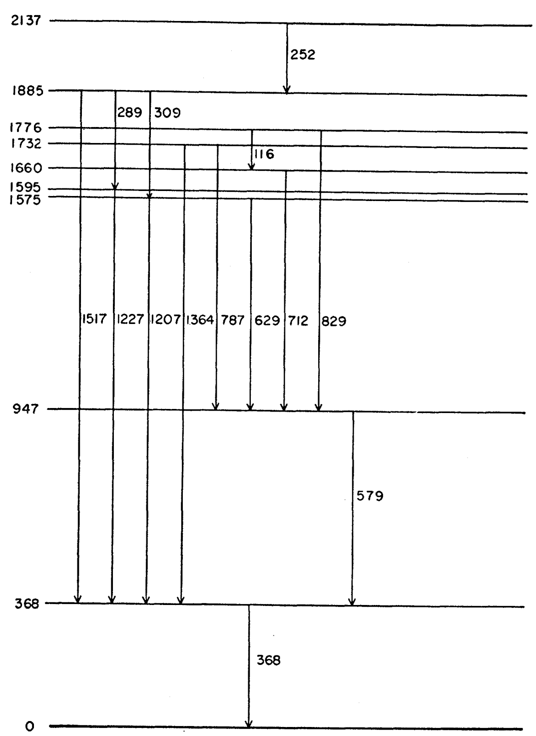


FIG. 4. Decay scheme following Tl^{200} decay as measured by Herrlander and Gerholm.

[2] Adyasevich, Groshev, and Demidov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow, July, 1955;* Physico-Mathematical Sciences (Akademiia Nauk, S.S.S.R., Moscow, 1955), p. 270; [English translation by Consultants Bureau, New York: U. S. Atomic Energy Commission Report TR-2435, 1956, p. 195].

[3] Henry E. Duckworth, Revs. Modern Phys. 29, 767 (1957).

[4] C. J. Herrlander and T. R. Gerholm, Nuclear Phys. 3, 161 (1957).

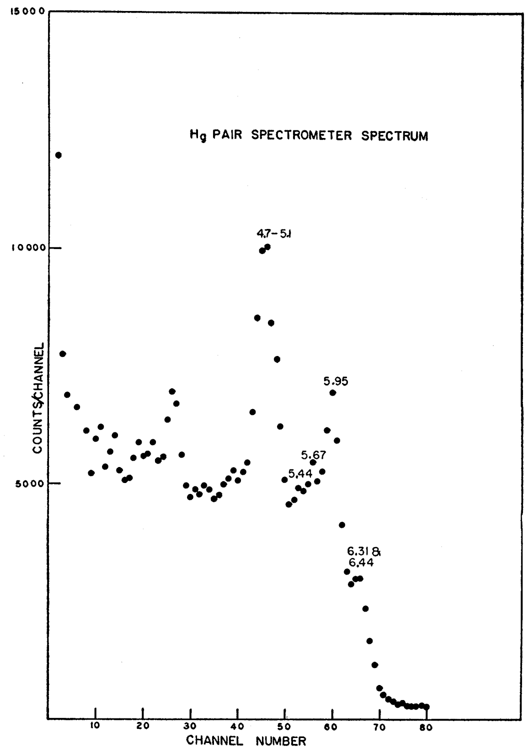


FIG. 5. Mercury capture γ-ray spectrum as measured by three-crystal pair spectrometer.

As can be seen from Fig. 4, no crossover transitions from the higher excited states to the ground state were observed. However, in the capture γ-ray spectrum, several lines are seen which appear to correspond to transitions from levels in that energy region to the ground state. H.G. refer to the A.G.D. work, and searched for ground-state crossover transitions, but failed to find any.

It was partially to resolve the above discrepancies that the present work was undertaken.

EXPERIMENTAL RESULTS

The spectrum observed with the three-crystal pair spectrometer is shown in Fig. 5. Radioactive sources were used to obtain a rough calibration for the spectrometer, and then a more exact calibration was obtained by identifying the strongest lines observed here with the stronger lines observed by A.G.D. (see Table I). The main features of the pair spectrometer spectrum relevant to the present work were the following:

(1) A broad plateau at about 6.4 Mev. This corresponds to the 6.31- and 6.44-Mev lines.

(2) A strong, sharp peak at about 6 Mev. This corresponds to the 5.99-Mev line.

(3) and (4) Two weak, but definite, lines between 5 and 6 Mev. These are the 5.44- and 5.67-Mev lines.

(5) A strong broad peak at about 5 Mev. This should consist of the four lines from 4.69 to 5.05 Mev.

(6) A peak at about 3.2 Mev. This is composed of the 3.14- and 3.25-Mev lines.

Coincidence spectra were taken with the pair spectrometer channeled at settings 1–5 above. For the broad peak at 5 Mev, coincidence spectra were taken with the pair spectrometer channeled on the low side of the peak, on the high side, and at the peak. These spectra were quite different, demonstrating that the peak was, indeed, composed of several lines.

The coincidence spectrum in the low-energy crystal with the pair spectrometer channeled from 6.25 to 6.55 Mev is shown in Fig. 6. The two peaks at ~1.25 Mev at ~1.65 Mev are both far too broad to consist of single lines. The 1.25-Mev group can be fitted by two lines of about equal intensity at 1.22 and 1.29 Mev.[5] A line of comparable strength at 1.36 Mev[5] can be excluded by the data. The higher-energy group is best fitted by three lines of energies 1.59, 1.65, and 1.73 Mev, though the crudeness of the data and an inadequate knowledge of the detailed response function of the crystal make it impossible to be certain of the presence of the 1.65-Mev line. The intensity of the 1.59-Mev line can be rather reliably estimated as being ~1.5–2 times as strong as the 1.22-Mev line (after correcting for the relative crystal peak efficiencies).

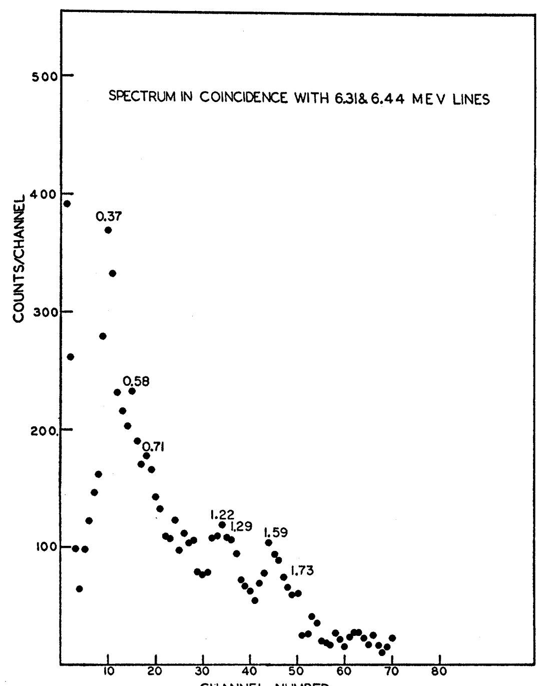


FIG. 6. Spectrum in coincidence with 6.25–6.55 Mev Hg capture gamma rays.

[5] The 1.29 line was previously mistakenly identified as the 1.36 line of H.G. R. E. Segel, Bull. Am. Phys. Soc. Ser. II, 3, 64 (1958).

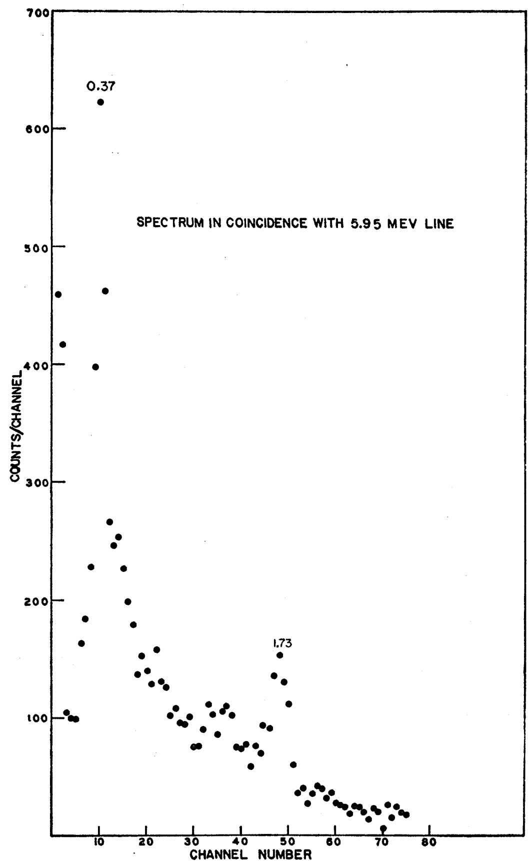


FIG. 7. Spectrum in coincidence with 5.95-Mev peak in Hg capture spectrum.

The remainder of the peak is best fitted by the 1.73-Mev line being $\sim\frac{1}{2}$ as intense as the 1.59-Mev line, and the 1.65-Mev line still weaker. A strong peak is seen at 0.37 Mev and probable indications of transitions at 0.58 and 0.71 Mev.

The only conclusion compatible with a neutron binding energy of about 8.06 Mev (a different binding energy is inconsistent with much of the other data) is for the 6.44-Mev gamma ray to be feeding a state at 1.59 Mev which decays $\sim$60% to the ground state and $\sim$40% by a 1.22-Mev gamma ray to the first excited state at 0.37 Mev. The 1.73-Mev state fed by the 6.31-Mev gamma ray appears to decay chiefly directly to the ground state. The 1.29-Mev line can only be explained as a transition from a state at 1.66 Mev to the 0.37-Mev state. A 1.66-Mev state is seen by H.G. (see Fig. 4) but they see it decaying only by a 0.71-Mev gamma ray through the 0.95-Mev state. The 0.71- and 0.58-Mev lines indicated in Fig. 6 would correspond to this mode of decay. The possible 1.66-Mev line would, of course, represent the crossover from this state. The 1.66-Mev state would then be fed by a 6.40-Mev gamma ray. From the published spectrum of A.G.D., it does not appear that such a line would have been resolved from the 6.31- and 6.44-Mev lines. Indeed, a "hump" does appear to be present in their spectrum at about the right place.

All the gamma rays indicated in the spectrum shown in Fig. 6 are consistent with the A.G.D. results. However, the crossover transitions from the 1.59, 1.73, and possibly 1.66-Mev states, the 1.29-Mev transition from the 1.66-Mev state to the 0.37-Mev state, and the absence of a 1.36-Mev gamma ray are in disagreement with the H.G. decay scheme. Some comments on these disagreements are given in the "Levels in Hg^{200}" section.

The spectrum in coincidence with the 5.99-Mev line is shown in Fig. 7. This spectrum shows two peaks: at 0.37 and 1.73 Mev. Both peak widths are consistent with their being due to single gamma rays. A cascade decay of the 2.10-Mev level through the 0.37-Mev level is, therefore, clearly implied. The total energy of the three gamma rays adds up to 8.09 Mev, which is a little high, suggesting that 5.96 Mev is a better value for the high-energy γ-ray energy. It is interesting to note the absence ($<10\%$ of the 1.73-Mev peak) of a peak at 2.10 Mev, the crossover energy. This can be taken as a direct experimental verification that the crossover lines seen in the decay of the lower-lying levels were not due to sum peaks. It is also interesting to note that the strong 1.73-Mev line seen by A.G.D. is in reality a doublet.

The spectrum in coincidence with the 5.67-Mev line showed a peak at 2.02 Mev as well as at 0.37 Mev. Again, a cascade through the first excited state is implied. All of the coincidence spectra showed a peak at 0.37 Mev, though this peak varied considerably in intensity. A portion of this peak was due to the low-energy tails from higher energy gamma rays in the pair spectrometer (see Fig. 1).

The spectrum in coincidence with the 5.44-Mev line showed peaks corresponding to gamma rays of energies 2.64, 1.73, 0.51, and 0.37 Mev. The 2.64-Mev line was the strongest, and represents the ground-state transition. Indications of a line at 0.51 Mev were found in all the spectra and are ascribed to annihilation radiation. However, the intensity of the 0.51-Mev line seen in this spectrum was greater by at least a factor 2 than it was in the spectrum in coincidence with 5.67 Mev. Furthermore, the presence of a 1.73-Mev line adds credence to a cascade through the 2.10-Mev level. However, this cascade cannot really be considered as being definitely established.

The spectra obtained in coincidence with $\sim$5.05 Mev is shown in Fig. 8 (a) and (b). The high-energy end of the spectrum shows indications for lines at 3.25, 3.00, and 2.89 Mev. A well-defined peak is seen at 2.02 Mev, and broad peaks centered at $\sim$1.25 and 1.65 Mev. Figure 8 (b) is also the spectrum in coincidence with $\sim$5.05 Mev, but with a higher gain on the low-energy counter. Here is seen a rather broad smear centered at ~1.25 Mev, and peaks at 0.93, 0.54, and 0.37 Mev. The peak at 0.54 Mev appears to be broadened on the low side, probably because of annihilation radiation.

The most reasonable conclusion from the data seems to be that the state at ~3 Mev decays primarily by a 2.02-Mev gamma ray (indicating that the 2.02-Mev line in the singles spectrum is really a doublet) to the 0.95-Mev state, which decays both directly to the ground state and through the first excited state. This is in contradiction to the H.G. data, which lists no crossover from the 0.95-Mev state. This point will be discussed in the "Levels in Hg^{200}" section. The best energy for the initial state is, therefore, about 2.97 Mev. This state also appears to have a weak transition directly to the ground state. The group at around 1.25 Mev probably is due to weak cascades through one or more of the states at ~1.5–1.8 Mev.

The 2.89-Mev line probably represents a transition from a state at this energy to the ground state. Such a state would be fed by a gamma ray at 5.17 Mev. While no such gamma ray is listed by A.G.D., the peak in their spectrum at 5.05 Mev appears to be broadened on the high side.

The 3.25-Mev line is almost certainly due to the strong 4.82–3.25 Mev cascade (see below).

The coincidence spectrum taken with the pair spectrometer set at the top of the broad 5-Mev peak (~4.82 Mev) showed chiefly a strong line at 3.25 Mev, implying a transition from the 3.25-Mev state directly to the ground state.

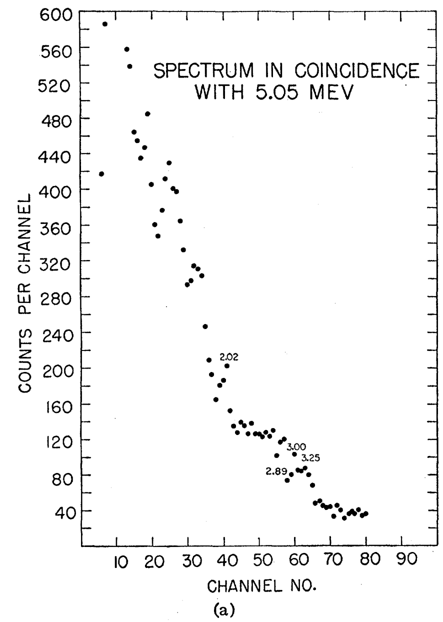
The coincidence spectrum taken with the pair spectrometer set to cover the 4.69-Mev region showed no strong lines >2.5 Mev. Lines were seen at 2.29 and 0.68 Mev and, as usual, 0.37 Mev. A 4.69–2.29–0.68–0.37 Mev cascade going through a state at ~1.05 Mev is, therefore, implied. A 1.05-Mev crossover transition is also indicated by the data, though it is not certain. A state at about this energy is indicated by the 6.95-Mev line of A.G.D. However, no state at this energy is seen in the H.G. work.

Again, weaker, unresolved lines at 1.2–1.8 Mev were observed.

The 7.66, 7.08, and 6.95-Mev lines seen by A.G.D. are too weak in intensity to be assigned to Hg^{200} with certainty. However, the neutron binding energy as calculated from the nuclear masses[3] is too low for these lines to be due to any of the mercury isotopes except Hg^{200} (8.06 Mev) or Hg^{202} (7.75 Mev). The low-lying levels of Hg^{202} are not sufficiently well established to eliminate this isotope as the source of these transitions.

As can be seen from Table I, the energy of the 7.66-Mev line is consistent with it feeding the well established 0.37-Mev level.

The intensities of these lines were too low to permit the usual pair spectrometer—3-in.×3-in. crystal—coincidence measurements. However, as these weak lines are the highest-energy lines present in the spectrum, it was possible to substitute a 3-in.×3-in. NaI(Tl) crystal for the pair spectrometer and channel on the full energy peaks. A spectrum taken in coincidence with the pulse-height region corresponding to 6.7–7.5 Mev is shown in Fig. 9. The accidental coincidences have been subtracted from this spectrum. The spectrum of Fig. 9 appears to be best interpreted as follows:



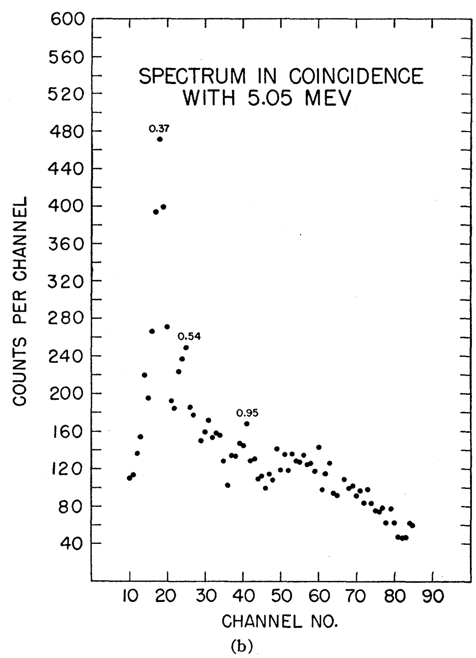


FIG. 8. (a) and (b) Spectra in coincidence with 5.00–5.20 Mev Hg capture gamma rays. The spectrum in Fig. 8 (b) goes up to 1.85 Mev.

1. The 0.68-Mev line represents a transition from a state at 1.05 Mev to the 0.37-Mev first excited state. 1.05 Mev is a bit, but not significantly, outside the value of 1.11 ± 0.05 implied for the energy of this state by the A.G.D. work. A better energy for the high-energy line is, therefore, 7.01 Mev, and this line can be assigned to Hg^{200}. A possible weak crossover transition is also seen.

2. The 0.95-Mev line represents a crossover from a state at this energy to the ground state. The peak at 0.53 Mev is definitely too broad to be due solely to annihilation radiation and, therefore, is due to a combination of annihilation radiation and a 0.58-Mev stopover transition. The presence of this annihilation radiation makes it impossible to estimate the relative strengths of the crossover and stopover transitions. The 7.08 line is, therefore, also assigned to Hg^{200}.

3. The 1.22 and 1.59 peaks are due to coincidences with the high-energy tail from the 6.44-Mev line. The 6.44-Mev line is ~100 times as strong as the 7.01- and 7.08-Mev lines, and, therefore, its presence would still be felt up into the region covered by the high-energy channel.

The decay scheme deduced by the present work is shown in Fig. 10. Table II gives the intensity of the cascades which were strong enough to be measured. These intensities should be taken only as fairly rough estimates.

LEVELS IN Hg^{200}

The experiment reported here, as well as the work of H.G. and A.G.D., each contains a large amount of detailed information. In order to correlate this information, this section will be devoted to analyzing the decay scheme in detail.

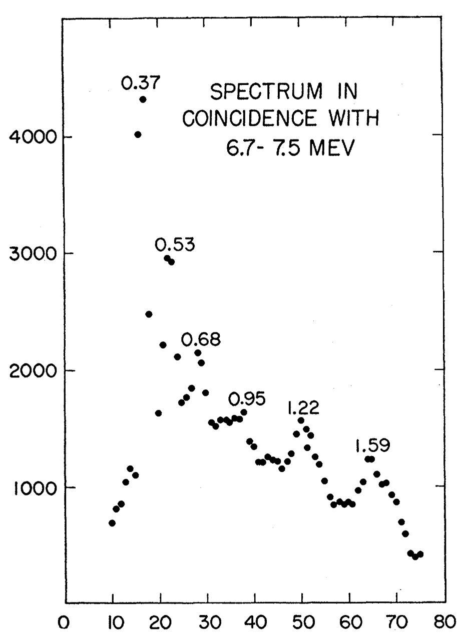


FIG. 9. Spectrum taken in coincidence with 3-in.×3-in. NaI(Tl) crystal set for 6.7–7.5 Mev.

There are several places in the "results" section in which discrepancies between the capture gamma-ray data and the H.G. decay scheme are indicated. Before proceeding to a more detailed analysis of the various data, a word is in order about the limitations of the various experiments.

A.G.D.—This work was done using a Compton recoil β spectrometer, with the electrons emerging in the forward direction being analyzed magnetically. The differential cross section for Compton electrons scattered in the forward direction is a monotonically increasing function of energy. Therefore, the energies and the intensities of the higher energy gamma rays can be expected to be the more precise in this experiment.

H.G.—Virtually all of the data presented by these authors was deduced from measurements on the internal conversion electrons. Therefore, the transitions which are most likely to have been missed in this work are those which are weakly converted.

Present work.—As mentioned in the "experimental technique" section, the response function as well as the poorer resolution is a disadvantage in NaI(Tl) spectrometer measurements. A monoenergetic gamma ray in the low-energy counter would give rise to a pulse-height distribution consisting of a lower-energy continuum as well as a full-energy peak. The full-energy peaks of less energetic gamma rays would, therefore, be imposed on the Compton tails of the higher-energy lines. The present experiment is, therefore, most likely to miss weak transitions in the presence of stronger, higher-energy ones.

With the above comments in mind, we now proceed to a discussion of the various levels.

Ground state.—The fact that Hg^{200} is an even-even nucleus assures a 0^+ assignment to this state.

8.06-*Mev capturing state.*—The $\frac{1}{2}^-$ spin (in the ensuing discussion, "spin" will be taken to include parity) of Hg^{199} limits the possible assignments to the capturing state to 0^- or 1^-. The absence of a ground-state transition, and the low intensity of the transition to the first excited state, indicate a 0^- assignment to the capturing

TABLE II. Intensity of the stronger γ-ray cascades seen in the present work.

Cascade (Mev)	Intensity[a]
6.44–1.59	3.3
6.44–1.22–0.37	1.8
6.40–1.29–0.37	1.7
6.31–1.73	3.1
5.95–1.73–0.37	10[a]
5.67–2.02–0.37	5.6
5.44–2.64	4.2
5.05–2.02–0.95	2.5
4.82–3.25	13
4.69–2.29–0.68–0.37	1.2

[a] Normalized to 10 for the 5.95–1.73–0.37 Mev cascade in order to facilitate comparison with the intensities in Table I.

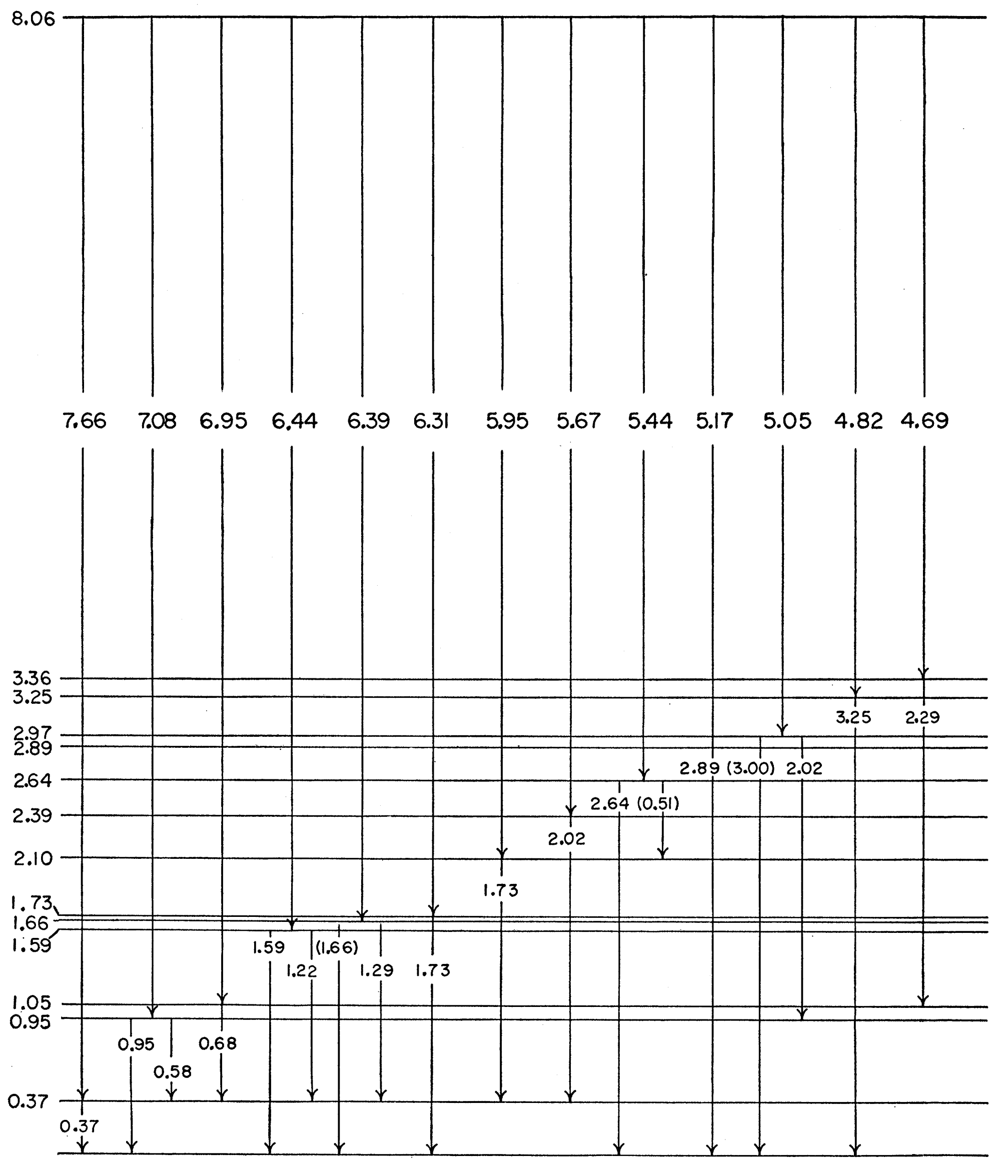


FIG. 10. γ-ray decay following thermal neutron capture as measured in the experiment reported here.

state. This assignment is strengthened by the enhancement of these transitions at the 34-volt resonance.[6]

Ground state of Tl^{200}.—H.G. assign 2^- to this state from the spectral shape and the $\log ft$ value of the positron decay to the ground state of Hg^{200}.

0.37-Mev level.—A 2^+ assignment is expected for this state from the systematics encountered for the first excited states in other even-even nuclei. This assignment is confirmed by Coulomb excitation measurements.[7] The intensity of the 7.66-Mev capture gamma ray feeding this state is consistent with an $M2$ transition.

0.95-Mev level.—A level at about this energy is seen in both the capture gamma-ray and the β-decay work. The level seen in the capture gamma-ray work appears to decay via both a crossover and a stopover transition, as witness the 7.08–0.95, 7.08–0.58–0.37, 5.05–2.02–0.95, and 5.02–2.02–0.58–0.37 Mev cascades. The relative strength of the stopover to the crossover is difficult to estimate because of the interference of annihilation radiation with the 0.58-Mev peak. However, they appear to be roughly comparable.

The fact that an allowed K capture to this level is not seen indicates that it must have positive parity. The intensity of the 7.08-Mev line is most consistent with quadrupole radiation and, therefore, the transition must be $M2$ and the spin of the 0.95-Mev state 2^+.

H.G. also found a level at 0.95 Mev. However, H.G. saw only a 0.58-Mev stopover emanating from this state. A search for conversion electrons corresponding to a 0.95-Mev gamma ray yielded a null result,

[6] H. H. Landon and E. R. Rae, Phys. Rev. **107**, 1333 (1957).
[7] Davis, Divatia, Lind, and Moffat, Phys. Rev. **103**, 1801 (1956).

TABLE III. Theoretical and observed conversion coefficients for (1^-, 2^-, or 3^-)-2^+ transitions.

E_γ (Mev)	Observed α_K	Theoretical[a] $E1$	$M2$
1.207	$(1.3\pm0.5)\times10^{-2}$	1.4×10^{-3}	1.8×10^{-2}
1.227	$(4\pm1)\times10^{-3}$	1.3×10^{-3}	1.7×10^{-2}
1.517	$(1.0\pm0.5)\times10^{-2}$	9.3×10^{-4}	1.0×10^{-2}

[a] See reference 8.

with an upper limit of about 1% being placed on the intensity of this conversion line relative to the K-conversion line corresponding to the 0.58-Mev gamma ray. On the basis of the absence of the crossover, H.G. assign a spin of 4^+ to this 0.95-Mev second excited state.

It is difficult to reconcile these data. One would be tempted to say that a 2^+–4^+ doublet exists at ~0.95 Mev. However, it is difficult to see why the 4^+ member of the doublet is preferentially populated following β decay. Furthermore, accepting 1^- spin assignments for the 1.66- and 1.73-Mev levels (see below), the 0.71- and 0.79-Mev transitions of H.G. appear inconsistent with a 4^+ assignment for the 0.95-Mev state. However, it must be noted that this state is primarily populated by the 0.83-Mev line in the H.G. decay scheme.

Considering all the evidence, there seems to be good grounds for saying that a 2^+ state exists at ~0.95 Mev. The possibility that there also exists a 4^+ state at about the same energy cannot be ruled out.

1.05-Mev level.—The evidence for this level from the capture gamma-ray work is similar to the evidence for the 0.95-Mev state. The 1.05-Mev level differs from the 0.95-Mev level in that the crossover transition appears to be much weaker, and perhaps absent entirely. The intensity of the 6.95-Mev line is most consistent with $M2$ radiation, though the possibility of the transition being $E3$ cannot be completely ruled out. If the crossover from the 1.05-Mev state is truly absent (~1% or less of the stopover), 3^+ is a possible spin for this state. However, a 2^+ assignment seems the more likely from the data. The absence of this level in the H.G. decay scheme is unexplained.

1.59-Mev level.—From the intensity of the lines listed by H.G., it can be inferred that all of the levels found by these workers above 1 Mev are fed by allowed K capture, and, therefore, must be 1^-, 2^-, or 3^-. The relatively strong capture gamma ray feeding the 1.59-Mev state implies a dipole transition, and, therefore, must be $M1$ and the 1.59-Mev state 1^-.

The decay of this state is puzzling as a ground-state as well as a first excited-state transition is seen in the present work, while only the first excited-state transition is seen by H.G. The discrepancy can be at least partially resolved by considering the multipolarity of the gamma rays involved.

All of the levels which are fed by allowed K capture can decay by $E1$ radiation to the 2^+ first excited state. H.G. measured the conversion coefficients for three of these first excited-state transitions, and their results are listed in Table III together with the theoretical values[8] for $E1$ and $M2$ radiation.

It can be seen from Table III that ~50% $M2$ admixture is required to fit these data.

The 1^- assignment to the 1.59-Mev state requires that the ground-state transition to be pure $E1$. $M2$ transitions are more highly converted than $E1$ transitions by about a factor of 10, and, therefore, even if the 1.59-Mev crossover gamma ray were twice as strong as the 1.22-Mev stopover, the conversion line corresponding to the crossover would be less than half the strength of the conversion line from the stopover. The intensity of the crossover conversion line should then have been somewhat, but not much, above the limit of detectability in the H.G. experiment. Considering the uncertainties in the intensity measurements in both experiments, it is reasonable that the 1.59-Mev conversion line was missed by H. G.

The decay seen in the present work is consistent with the A.G.D. spectrum, which lists strong lines of comparable intensities at 1.22 and 1.59 Mev.

1.65-Mev level.—This level is also populated directly by K capture and by a capture gamma ray and, therefore, must have a spin 1^-. This level is apparently de-excited chiefly by a 1.29-Mev transition through the first excited state. This 1.29-Mev transition was not seen in the H.G. work. Were this transition largely $E1$, it again could be weakly enough converted so as to have been overlooked.

A crossover transition is also probable, but in this case appears to be weaker than the stopover. This would be in agreement with the A.G.D. spectrum which lists a strong line at 1.29 Mev and a considerably weaker line at ~1.62 Mev. Should the 1.65-Mev crossover be present, it must be pure $E1$, and the conversion line too weak to have been detected.

H.G. see this state decaying through the 0.95-Mev state. Indications for this cascade are seen in the present work.

1.73-Mev level.—This level is excited through both modes of excitation and so again, a spin of 1^- is preferred. Again, a crossover transition is seen in the gamma-ray work but not in the conversion-electron studies. The same reasoning as is applied to the decay of the 1.59- and 1.65-Mev levels can be used to explain the apparent discrepancy here.

A stopover transition of 1.36 Mev is seen by H.G. but not in either the present study or in the A.G.D. spectrum. An upper limit for the ratio of the stopover to the crossover is difficult to estimate in either capture gamma experiment due to contamination of the 1.73-Mev peak by the other line at about 1.73 Mev in the strong 5.95–1.73–0.37 Mev cascade (see "2.10-Mev level" below). The lack of knowledge of this ratio for the

[8] L. A. Sliv and J. M. Band (privately circulated tables).

gamma rays renders it impossible to state whether or not the conversion-electron data are consistent with the gamma-ray data.

The above discussion implies that the strength of the 6.31–1.73 Mev cascade as listed in Table II should more realistically be considered an upper limit.

1.57-Mev level.—The energy resolution in the capture gamma-ray work is insufficient to separate the 1.59- and 1.57-Mev levels. In the H.G. work, the 1.21-Mev line emanating from the 1.57-Mev state is about a factor of two stronger than the 1.23-Mev line emanating from the 1.59-Mev state. If one assumes that it is the 1.57-Mev level that is fed by the capture gamma ray, then there must be an accompanying 1.57-Mev line of strength comparable to the 1.21-Mev line. The conversion line from this 1.57-Mev transition should have been strong enough to be detected by H.G. Furthermore, the presence of this hypothetical 1.57-Mev line would imply a far stronger K capture to the 1.57-Mev state than to any of the other states. For these reasons, it is concluded that it is the 1.59-Mev level that is chiefly fed by the 6.44-Mev capture gamma ray.

The absence of a strong capture gamma ray to the 1.57-Mev state indicates that its spin is >1, and as this level is reached by an allowed K capture, a spin assignment of either 2^- or 3^- is indicated.

1.78-Mev level.—This level is also reached by an allowed K capture but not strongly fed by a capture gamma ray. As with the 1.57-Mev level, a spin of 2^- or 3^- is indicated.

The absence of a conversion line corresponding to a transition from this state to the 0.37-Mev first excited state is noteworthy. Either both the $E1$ and $M2$ transition probabilities must be sufficiently retarded to suppress the transition, or the line is present but almost pure $E1$ and, therefore, weakly converted.

It is also interesting to note that the conversion coefficient for the rather strong 0.83-Mev transition to the 0.95-Mev state is best fitted by an $E1+M2$ mixture of approximately equal proportions.

1.89-Mev level.—This is another state which is fed by an allowed K capture but not by a capture gamma ray. A 2^- or 3^- assignment is, therefore, once more indicated.

2.10-Mev level.—The energy resolution of A.G.D. is sufficient to distinguish this level from the 2.14-Mev level of H.G. This 2.10-Mev level is strongly fed by a capture gamma ray, but not by an allowed K capture. 1^+ is, therefore, the most probable spin assignment and the 5.95-Mev line $E1$.

This state decays chiefly by the 1.73-Mev $(M1+E2)$ transition to the first excited state, with the 2.10-Mev pure $M1$ ground-state transition much weaker.

The strong 1.73-Mev line of A.G.D. is then in reality a doublet, with the major contribution probably coming from the transition from the 2.10 to the 0.37-Mev state. A much weaker 2.10-Mev line is seen by A.G.D., which is consistent with the present work.

TABLE IV. Spins of states discussed.

Level (Mev)	Probable spin	Level (Mev)	Probable spin
0	0^+	1.66	1^-
0.37	2^+	1.73	1^-
0.95	2^+	1.77	$2^-, 3^-$
1.05	$(2)^+$	1.89	$2^-, 3^-$
1.57	$2^-, 3^-$	2.10	1^+
1.59	1^-	2.14	$(1)^-$

2.14-Mev level.—The 5.88-Mev line of A.G.D., of which they seem to be a bit uncertain, is of the correct energy to feed this state. Since this state is also fed by an allowed K capture, a 1^- assignment is again indicated. The energy resolution of the present work was too poor to separate the 5.88-Mev line from the strong 5.95-Mev line, and, therefore, cascades initiated by this 5.88-gamma ray were not seen. The uncertainty in the capture gamma-ray decay through this state renders its spin assignment doubtful.

Higher levels.—The total β-decay energy available is about 2.46 Mev, and therefore, states of higher excitation could not be reached by K capture. The 2.39-Mev really also falls into this category, as the decay energy to this state is so small that a capture to this state would be prohibitively weak.

The information about the states which can be reached only through the capture gamma rays is insufficient to allow definitive spin assignments. However, the strength of the transitions to the 2.39, 2.64, 2.97, 3.25, and 3.36-Mev states suggest dipole radiation and, therefore, a spin of 1 is implied for these states.

All of the lower-energy gamma rays reported here correspond to lines in the spectrum of A.G.D. Most of the stronger lines in the A.G.D. spectrum appear in the decay scheme of the present work. The 1.73- and 2.02-Mev lines each appear in two places in the decay scheme and are, therefore, doublets.

The probable spin assignments for the states discussed in this section is given in Table IV.

Finally, it must be remarked that capture gamma-ray transitions to higher-spin states is severely inhibited, as to a lesser extent are β-decay transitions, and, therefore, the preponderence of low-spin states observed is not necessarily of significance.

TRANSITION PROBABILITIES

It is well known that electromagnetic transition probabilities can be calculated under the assumption that the transitions are solely due to single-nucleon transitions between single-particle orbits.[9] It is equally well known that these estimates are accurate even to an order of magnitude in only the most favorable

[9] V. F. Weisskopf, Phys. Rev. 83, 1073 (1951).

TABLE V. Properties of some of the high-energy gamma rays.

E_γ	Multipolarity	Γ_γ (ev)	Γ_γ-calculated (ev)
7.66	$M2$	2×10^{-4}	4×10^{-5}
7.08	$M2$	7×10^{-5}	4×10^{-5}
6.47[a]	$M1$	5×10^{-3}	3×10^{-3}
6.39[a]	$M1$	5×10^{-3}	3×10^{-3}
6.31	$M1$	5×10^{-3}	3×10^{-3}
5.95	$E1$	2×10^{-2}	3×10^{-1}

[a] It is assumed that the 6.44-Mev line of A.G.D. is split equally into the 6.47- and 6.39-Mev lines of the present work.

situations. However, they provide a convenient "yardstick" against which to compare the experimental values and, therefore, the discussion in this section will be given chiefly in terms of these single-particle estimates.

A striking feature in the relative transition probabilities is illustrated in Table III, where it is shown that the conversion coefficient measurements require high $M2$ admixtures into certain allowed $E1$ transitions. Assuming that the $M2$ transitions proceed at normal (i.e., single-particle) speed, these data would indicate a retardation of $\sim10^6$ for the $E1$ transitions. It should not be assumed, however, that all the allowed $E1$ transitions show these large $M2$ admixtures, as it is those lines in which the large amount of $M2$ is present that are the more strongly converted and, therefore, the most likely to have been detected by H.G. In fact, it appears likely that transitions such as the 1.28-Mev transition between the 1.66- and 0.37-Mev states were missed by H.G. because they are more nearly pure $E1$ and, therefore, weakly converted.

The evidence on the $E1$ transition rates between low-lying levels can perhaps best be summarized by saying that for at least several of the transitions the $E1$ is severely inhibited.

Information about the $E2$ transition probabilities can be inferred from the decay of the 2.10-Mev state. In the previous section, reasons are given for assigning a spin of 1^+ to this state. If this assignment is accepted, the decay to the first excited state would be $(M1+E2)$ while the ground-state decay would be pure $M1$. The preponderence of decay to the first excited state implies an enhancement of the $E2$ transition probability relative to that of the $M1$. Assuming that the $M1$ transitions to both the ground state and the first excited state proceed at normal speed, the failure to observe the ground-state transition in the present work implies an $E2$ enhancement of $>10^2$. Large $E2$ enhancements are seen in other nuclei for which collective effects are important.

In the "Levels in Hg^{200}" section, spin assignments are made for several of the low-lying levels. The 0^- spin of the capturing state assures that the transitions to these low-lying levels will be of a single, pure multipolarity and, therefore, if the spin of the final state is known, the multipolarity of the transition is completely determined.

Table V lists those gamma rays eminating from the capturing state whose multipolarity has been determined. A total Γ_γ (conforming to the usual practice in discussions relating to this region of a nucleus we now refer to radiation width, Γ_γ, instead of transition probabilities; the radiation widths are, of course, directly proportional to the transition probabilities) of 0.225 electron volts is assumed in determining the partial radiative widths and the γ-ray intensities of A.G.D. are used. The theoretical widths are calculated from the estimate of Weisskopf[9] with the correction factor of D/D_0 as given in Blatt and Weisskopf.[10] A level spacing D of 300 electron volts was assumed and D_0 was taken to be 0.5 Mev.[11]

The data tabulated in Table V indicate that the $M1$ and $M2$ widths are greater than the calculated widths by about a factor of 2, while the $E1$ width is smaller by about a factor of 10. The agreement obtained for the magnetic transitions is certainly as good as can be expected considering the crudeness of the calculation. The $M1:M2$ ratio is in very good agreement with the single-particle estimate. A reduction of the $E1$ width by about a factor of 10 is indicated. While the radiative width of only one $E1$ transition is given, it corresponds to one of the strongest lines in the spectrum. If less inhibited $E1$ transitions were present, they would have showed up as stronger lines.

Kinsey,[12] on the basis of admittedly meager evidence, remarks that, in general, $M1$ capture gamma rays appear to be lower by about a factor of 10 than the Weisskopf estimate, while for even-charge nuclei, $E1$ transitions appear to be in closer agreement. In the present experiment the $M1$ transitions seem to be in good agreement with the Weisskopf estimate, while the $E1$ transitions are too low. It is clear that more cases will have to be studied before definitive systematics as to radiative partial widths are established.

ACKNOWLEDGMENTS

The instrumentation of this experiment was a long and arduous task in which the author was fortunate to have the assistance of many individuals. The invaluable assistance of Robert Chase with the numerous electronics problems is gratefully acknowledged. Thanks are also due the members of the Aeronautical Research Laboratory group at Brookhaven for their many services.

[10] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[11] This is the value suggested in reference 10. The values of D and Γ_γ are the same as those taken by A.G.D.

[12] B. B. Kinsey, in *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. XXV.

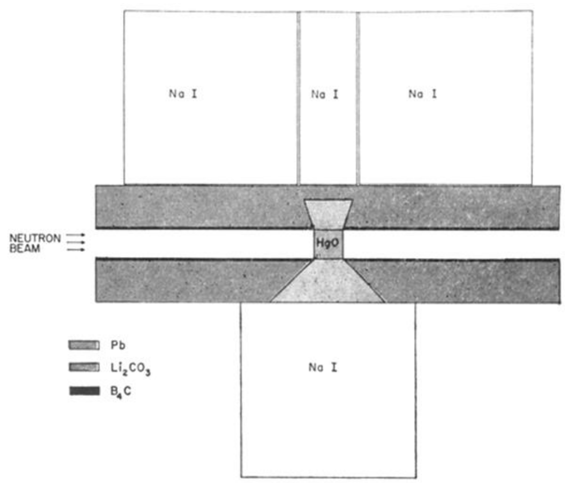


FIG. 2. Diagram of experimental geometry.