spectively. It is of interest to compare these transitions with the probably analogous transitions from the 2.16-Mev state[27,28] in Ni^{60} and the 2.46-Mev state[27,29] in Ni^{58}. Table VI summarizes this comparison; the similarity of the energy ratios is striking[30] and has also been found for similar levels[31] in Zn^{64}, Zn^{66}, and Zn^{68}. The reduced transition probabilities in Table VI have been calculated by assuming the second excited state to be 2^+ and assuming the $M1$ contribution to the transition from the second excited to the first excited state to be negligible.[32]

TABLE VI. Similarities in e-e Ni nuclei.[a]

Nucleus	Energy of excited states: First E_2 (Mev)	Second E_2' (Mev)	E_2'/E_2	Reduced transition probability $\frac{B(E2;2'\to 0)}{B(E2;2'\to 2)}$
Ni^{58}	1.453[b]	2.456	1.69	... [c]
Ni^{60}	1.329	2.161	1.63	(0.003)[d]
Ni^{62}	1.171	2.047	1.74	(~0.01)[e]

[a] The notation used is the same as that of reference 32.
[b] All energy values taken from references 27 and Gossett, Windham, Phillips, and Schiffer, Phys. Rev. 103, 1321 (1956).
[c] Only the transition between second and first excited states has been seen up to now (see reference 29).
[d] Intensity ratio from reference 28.
[e] Intensity ratio from present work.

[28] Van Lieshout, Nussbaum, Nijgh, and Wapstra, Phys. Rev. 93, 255 (1954); Nussbaum, Van Lieshout, Wapstra, Verster, Ten Haaf, Nijgh, and Ornstein, Physica 20, 555 (1954).
[29] R. M. Sinclair, Phys. Rev. 102, 461 (1956).
[30] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. 98, 212 (1955); J. J. Kraushaar and M. Goldhaber, Phys. Rev. 89, 1081 (1953).
[31] D. J. Horen and W. E. Meyerhof (to be published). In these nuclei the energy ratio is close to 1.8 and not 2.3 as was previously thought (see reference 32).
[32] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. 28, 432 (1956); see especially Table V, 6.

PHYSICAL REVIEW VOLUME 107, NUMBER 5 SEPTEMBER 1, 1957

Gamma Radiation from Resonance Neutron Capture in Mercury

H. H. LANDON,* *Brookhaven National Laboratory, Upton, New York*

AND

E. R. RAE, *Atomic Energy Research Establishment, Harwell, England*

(Received May 31, 1957)

An experiment has been performed to detect individual high-energy gamma rays associated with resonance capture in mercury, using an electron linear accelerator as a pulsed neutron source. The gamma-ray spectrum from the 34-ev resonance in the compound nucleus Hg^{200} has intense components of higher energy than does the spectrum from thermal capture in this isotope. From this it can be inferred that the spin of the 34-ev resonance is most probably 1 with negative parity.

INTRODUCTION

An investigation has been undertaken, using the A.E.R.E. linear electron accelerator[1] as a pulsed neutron source, to study the possibilities of observing individual high-energy capture gamma rays associated with resonance neutron capture. One of the pressing problems in slow, i.e., resonance energy neutron physics, has been the determination of spins associated with the individual sharp resonances in the compound nucleus, particularly the determination of the spin of more than one resonance in a single isotope. The problem in principle is straightforward. Accurate measurements of both total and scattering cross sections give unambiguous choices of all the Breit-Wigner parameters, including the spin. The scattering measurements, however, have proved to be very difficult, particularly when the level spacing is sufficiently small to permit observation of several resonances in a single isotope.[2] For some time we have wished to know what could be achieved by somewhat different approaches, utilizing differences in the decay schemes of the compound nucleus which might depend upon spin. Variations in the population of isomeric states have been observed[3] when activation is made through selected resonance states of the compound nucleus. It might be hoped that measurements of this type would show a division into two distinct groups from which the spins might be inferred after the establishment of at least one spin by a more direct method. One would certainly expect that the capture gamma-ray spectrum itself would change with the spin, although it has been evident for some time that such changes are not always obvious or easy to measure. We have felt, however, that if one could choose individual gamma rays, presumably of high energy, which originate at the

* Research performed at the Atomic Energy Research Establishment, Harwell, England, while on leave of absence from Brookhaven National Laboratory.
[1] E. R. Wiblin, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva* (United Nations, New York, 1956), Vol. 4, p. 35.
[2] E. R. Rae, Physica 22, 1131 (1956).
[3] V. L. Sailor (private communication); R. E. Wood, Phys. Rev. 95, 453 (1954).

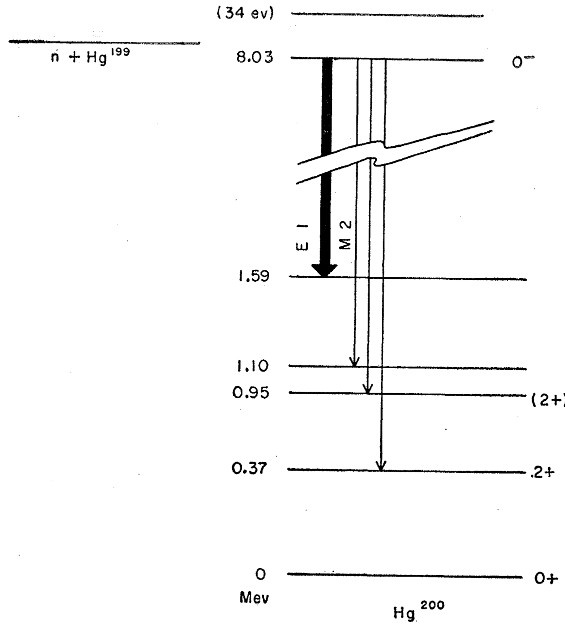

FIG. 1. Schematic diagram of the level structure of Hg^{200} as reported by Adyasevich *et al.* in reference 4.

capturing state and decay to a well-isolated low-lying state, and establish the multipolarity of these, then one would have made a direct attack upon the problem of the spin of the compound state. One needs for this, of course, rather special knowledge of the capture gamma-ray spectra, measurements which have themselves been difficult. In particular the spectra have been unknown for just those cases where the density of levels near the capturing state is interestingly large. The recent results of Adyasevich *et al.*[4] for Hg are particularly interesting and appear schematically in Fig. 1.

The thermal capture of Hg is dominated by a strong negative energy level[5] in Hg^{199}. The binding energy, as established by the capture gamma-ray results, is 8.03 Mev. No transition having the full binding energy, however, is observed. Since the even-even Hg^{200} has a ground state spin of 0^+, the absence of a ground state transition is strong evidence for assigning the spin of the capturing state as 0^-.[6] This assignment is strengthened by the absence of strong transitions to the first two excited states which have been assigned 2^+.[7]

Since the 0–0 transition is forbidden, the presence of an 8-Mev transition from a capturing state would unambiguously establish the spin of that state as 1^-. This transition would, of course, be $E1$ and consequently intense. The problem of detecting at 8.0-Mev gamma ray with good efficiency and resolution is not easy, but the problem is simplified by the existing scheme of low-lying states of Hg^{200}. Gamma rays from a capturing 0^- state to the first two excited states are $M2$ and consequently weak compared to $E1$. It is in fact observed by Adyasevich *et al.*[4] that no transition of $E1$ speed is seen above about 6.5 Mev. We have therefore set out to detect individual high-energy gamma rays associated with the decay of the well-known virtual level in Hg^{200} at 34 ev.[8,9]

MEASUREMENTS

A schematic diagram of the apparatus is shown in Fig. 2. The details of the operation of the linear accelerator as a pulsed neutron source for cross-section studies have been published.[1] For the present experiment[10] a sample of about 100 grams of natural mercuric oxide contained in a circular thin aluminum can 3.1 inches in diameter, was irradiated at the 11.5-meter station by the pulsed neutron beam. Three suitably shielded NaI(Tl) scintillation detectors surrounded the target. Pulses from these detectors were linearly amplified before being admitted to a single-channel discriminator. The pulses selected by the discrimator were time sorted in a 100-channel time-delay analyzer to permit selection of the flight time of the neutron whose capture in the mercury had given rise to the pulse in the gamma-ray detector. The type of data obtained for a particular bias setting of the discriminator is shown in Fig. 3. The resonance structure of natural Hg is clearly seen. The most probable isotopic assignment of the resonances according to reference 9, is shown. When the cadmium filter normally present in the beam is removed, curves such as that shown in Fig. 4 are

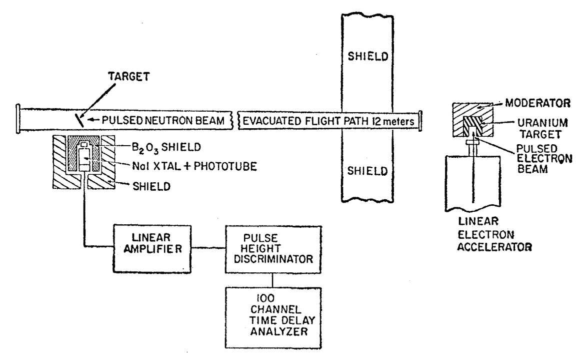

FIG. 2. Schematic diagram of the experimental apparatus associated with the neutron capture gamma-ray observation.

[4] Adyasevich, Groshev, and Demidov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on Peaceful Uses of Atomic Energy, July 1–5, 1955*, Session of Division of Physico-Mathematical Sciences (Akademiia Nauk, S.S.S.R. Moscow, 1955) [translated by the Consultants Bureau, New York, 1955, p. 195].

[5] W. W. Havens, Jr., and L. J. Rainwater, Phys. Rev. **70**, 154 (1946).

[6] The ground state spin of the target Hg^{199} has been assigned $\frac{1}{2}$ by H. Schüler and E. G. Jones, Z. Physik **74**, 631 (1932). Assuming the negative parity assignment of the shell model, *s*-wave neutrons can excite only 0^- and 1^- compound-nucleus states.

[7] Bergström, Hill, and DePasquali, Phys. Rev. **92**, 918 (1953).

[8] J. S. Levin and D. J. Hughes, Phys. Rev. **101**, 1328 (1956).

[9] R. R. Palmer and L. M. Bollinger, Phys. Rev. **102**, 228 (1956).

[10] Similar techniques for detecting low-energy gamma rays have been reported by Bennett, Walters, Fenstermacher, and Rosler, Bull. Am. Phys. Soc. Ser. II, **1**, 62 (1956).

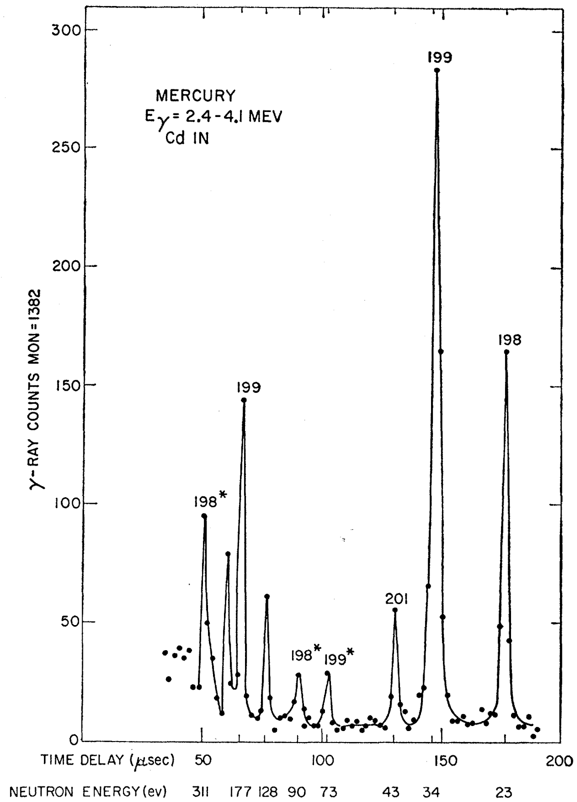

FIG. 3. Neutron capture gamma-ray counts *versus* neutron time of flight. Resonance energies are shown in electron volts. The isotopic assignments are taken from Palmer and Bollinger, reference 9. The asterisk signifies tentative assignments.

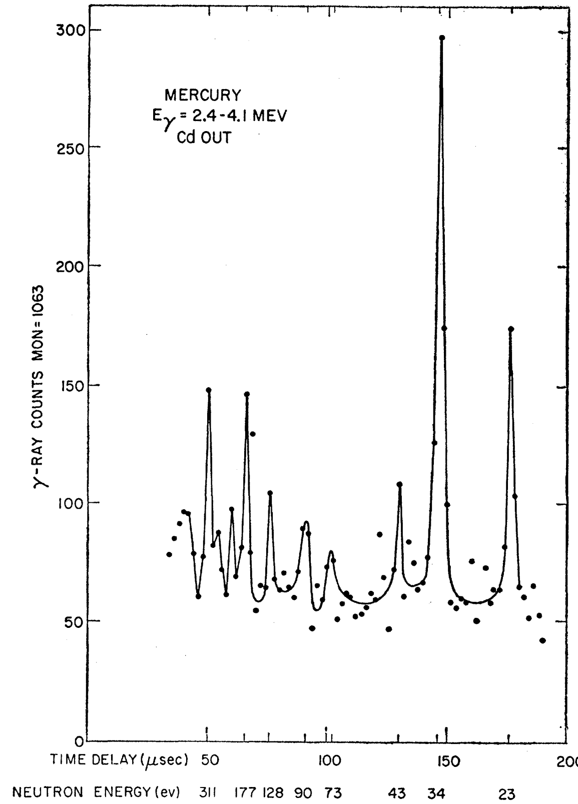

FIG. 4. Neutron capture gamma-ray counts *versus* neutron time of flight.

obtained. The resonance structure is still clearly seen, but an apparent large increase in the background counting rate is observed. These extra counts are due to the capture of very slow thermal neutrons whose flight time is greater than the cycling time of the spectrometer and which are normally removed by the cadmium filter. The gamma rays corresponding to the extra counts are therefore due to the capture of thermal neutrons by the mercury sample.

The principle of the experiment was to determine the ratio of the number of counts observed in a resonance peak to the number of counts associated with thermal capture, and to observe the variation in this ratio as the discriminator bias was increased. The bias setting of the discriminator determines the amplitude of the pulse obtained from the scintillation detectors, and so the amount of energy dissipated in the detectors by the capture gamma rays. The system was calibrated by using standard gamma-ray sources. The Cs^{137} line at 0.66 Mev was used for setting up the apparatus each day, a standard attenuator of 20 db normally present in the amplifier being removed during the calibration runs. The gamma ray of 4.4 Mev from the reaction $Be^9(\alpha,n)C^{12}$ was also used to check the linearity of the system up to that energy. Mercury gamma rays were observed, however, up to a bias setting corresponding to 9.0 Mev, thus indicating an uncertainty of approximately 1 Mev in the energy scale. Careful background studies were made both with the mercury sample replaced by an empty aluminum can and by a nonresonant scatterer of neutrons. Results are reported only for the strong resonance at 34 ev since the counting statistics achieved at the other two resonances were inadequate. Typical running time was approximately one hour per run for each bias setting.

RESULTS

The results are summarized in Fig. 5. A change in the character of the gamma radiation associated with the 34-ev resonance is clearly indicated. Gamma rays are seen from this state up to the limit of the binding energy, while intense radiation from thermal capture is not seen above approximately 6.5 Mev. Above this energy the ratio of thermal to resonance capture gamma rays approaches zero. The statistics associated with the ratio measurement are adequate to show definitely the change in the spectra. This result indicates that the spectrum of gamma rays from the 34-ev resonance is harder or more energetic than that from the thermal capture and implies the presence of strong radiation to the lowest lying states of Hg^{200}. We consequently infer

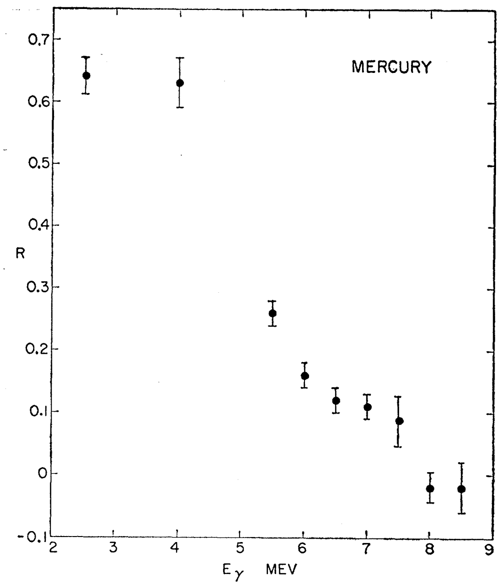

FIG. 5. The ratio R of gamma-ray counts due to thermal and 34-ev resonance neutron capture *versus* the energy of the gamma rays detected. The ordinate scale is arbitrary to the extent that the energy interval of thermal neutrons detected was arbitrary.

that the spin of the 34-ev resonance must be 1 with negative parity. A further series of measurements was undertaken by one of us (E.R.R.) to measure the entire pulse-height spectrum of events detected in the NaI counters while time sorting these events according to neutron energy. This was achieved by the use of a magnetic-tape recording technique[11] and also by direct recording of the pulse-height spectrum in a 100-channel pulse-height analyzer.[12] The curves obtained by the latter technique, together with the background pulse-height spectrum are shown in Fig. 6.

The apparatus was calibrated by using the 4.4-Mev gamma ray from $Be^9(\alpha,n)C^{12}$ and the 7.9-Mev gamma ray from the capture of thermal neutrons in copper, and it appears that the gamma-ray spectrum from the 34-ev neutrons extends to an energy of about 8.0 Mev. This indicates strong radiation to the lowest states in the Hg^{200} nucleus, including the ground state.

DISCUSSION

In addition to the information that one can obtain about the spin of compound-nucleus resonances, it should be mentioned that it is or soon will be possible to obtain other interesting results using these techniques. If one can observe individual high-energy gamma rays associated with the decay of a particular selected resonance of the compound nucleus one can measure the relative transition probability of this decay and consequently the distribution of partial widths for this gamma transition much as one does in the case of neutron-scattering partial widths. In addition, if one can select the transition from the individual resonance, then it should be possible to observe interference phenomena in the capture cross section. That is, if we restrict the number of exit channels in the capture process to a relatively small number, then interference effects between individual

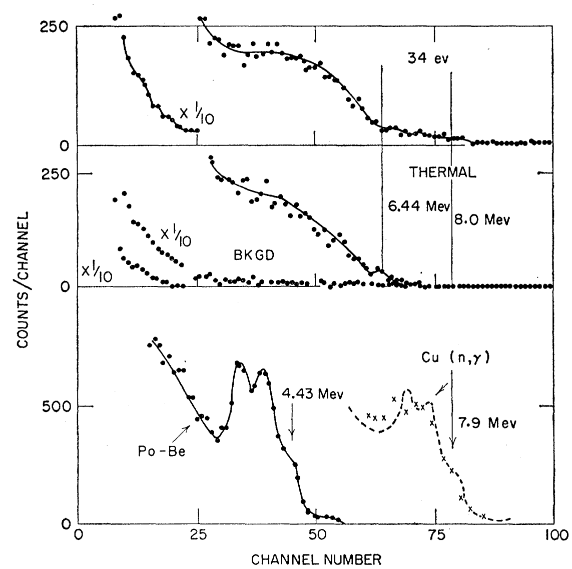

FIG. 6. The gamma-ray pulse-height spectrum observed for both thermal-neutron and 34-ev resonance neutron capture. The background spectrum is shown as well as the calibration spectra. The dotted $Cu(n\gamma)$ curve is based on an experimental line shape and results by G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).

resonances will show up. Such interference effects are not presently seen in this process because of the multiplicity of exit channels open in the normal capture experiment.

ACKNOWLEDGMENTS

One of us (H.H.L.) wishes to express appreciation to the Atomic Energy Research Establishment, Harwell, England for the opportunity to work there during the course of this experiment.

[11] E. R. Rae and F. Firk, Nuclear Instr. (to be published).
[12] K. Kandiah, Proc. Inst. Elec. Engrs. (to be published).