## Brief Reports

*Brief Reports are short papers which report on completed research or are addenda to papers previously published in the* **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

# Electromagnetic transitions in $^{205}$Hg

K. H. Maier
*Hahn-Meitner Institut für Kernforschung, D-1000 Berlin, West Germany*

W. Stöffl* and R. K. Sheline
*Florida State University, Tallahassee, Florida 32306*

J. A. Becker, D. J. Decman, E. A. Henry,
L. G. Mann, and G. L. Struble
*Lawrence Livermore National Laboratory,*
*Livermore, California 94550*

L. E. Ussery, J. A. Cizewski,† and B. H. Erkkila
*Los Alamos National Laboratory,*
*Los Alamos, New Mexico 87545*
(Received 25 March 1985)

Gamma-ray transitions in $^{205}$Hg have been observed in the $^{204}$Hg(t,d)$^{205}$Hg reaction. A partial level scheme is obtained. Delayed gamma rays exhibiting $\tau_m = (1.59 \pm 0.06) \times 10^{-3}$ s are observed; the identification with the decay of the $i_{13/2}$ neutron hole state is suggested.

Matrix elements involving proton-hole states are an important input for nuclear model calculations. In the $^{208}$Pb region, experimental measurements of these matrix elements are incomplete. Single-hole state energies have been measured in $^{207}$Tl and some $(\pi^{-1}\nu^{1})$- and $(\pi^{-1}\nu^{-1})$-interaction energies have been determined in other Tl isotopes. The interaction between two proton holes can be deduced from measurements made on Hg isotopes with neutron number near 126. There exist, however, very little experimental data. Consequently, there is an uncertainty in describing 2p-2h excitations of the $^{208}$Pb nucleus and the properties influenced by these excitations such as electric quadrupole moments and transitions. We report here some work on low excitation states in $^{205}$Hg.

$^{205}$Hg is described in the shell-model framework as two proton holes and one neutron hole in the closed $^{208}$Pb core. The low excitation three-hole states can be calculated quite well in the shell model, as Silvestre-Brac and Boisson[1] have done. Experimentally, excited states of $^{205}$Hg have been studied only with the $^{204}$Hg(d,p)$^{205}$Hg reaction.[2,3] This reaction preferentially populates one-particle four-hole states. The low-lying three-hole levels are only weakly excited; because of this and the effects of target impurities, Moyer[2] found it difficult to interpret the measured proton angular distributions reliably enough to assign spins. Thus, only the excitation energies of some low-lying levels are known in this nucleus. Data on gamma transitions have not been reported. We have used the $^{204}$Hg(t,d)$^{205}$Hg reaction and the techniques of in-beam gamma-ray spectroscopy to study $^{205}$Hg. In the following we present our data on gamma-ray transitions in $^{205}$Hg, and the partial level scheme we deduce based upon this and previous work.

The data for $^{205}$Hg were collected in the following experiments performed at the Los Alamos National Laboratory Van de Graaff facility:

(1) A gamma-gamma-time coincidence experiment at $E_t = 16$ MeV.

(2) Gamma-ray angular distribution measurements at $E_t = 16$ MeV.

(3) Two pulsed-beam experiments. The first was performed at $E_t = 14.2$ MeV. The pulse width was $\sim 1$ ns, and the pulse interval was 12.8 $\mu$s. In the second measurement, which was designed to measure lifetimes in the millisecond range, the 16 MeV beam was deflected on and off target at intervals of 25 ms. Data were collected only when the beam was off.

The target consisted of metallic liquid Hg on a copper backing. The Hg target was enriched in $^{204}$Hg to 98.2%. Gamma radiation was detected with Ge spectrometers. For energy calibration we used sources of $^{60}$Co, $^{57}$Co, $^{137}$Cs, and $^{241}$Am concurrently with the in-beam $^{204}$Hg target. The general features of in-beam gamma-ray spectroscopy with triton beams and of our experimental arrangement are described in Refs. 4 and 5. Further details of the present experiment are presented in reports of the concurrent measurements of $^{205}$Tl and $^{206}$Hg (Refs. 6–8).

The gamma rays that we assign to $^{205}$Hg are listed in Table I. The energies of the 879- and 1016-keV gamma rays were determined relative to other $^{205}$Hg gamma rays from coincidence spectra gated on the 379-, 501-, and 967-keV transitions, since the 879-keV gamma ray was not detectable and the 1016 was part of an unresolved doublet in the ungated spectra. We assign the 379- and 468-keV gamma rays as transitions to the ground state of this nu-

 

TABLE I. $^{205}$Hg gamma rays, energy levels, and angular distribution coefficients deduced from the $^{204}$Hg(t,d) reaction.

| $E_\gamma$ (keV) | $I_\gamma$[a] | $E_i$ (keV) | $E_f$ (keV) | $A_2$[b] | Coincident gamma rays (keV) |
|---|---|---|---|---|---|
| 379.42(11) | 18.5(2) | 379.42(11) | 0 | +0.18(1) | 501 967 1016<br>(161 164 188 506.5 567 945)[c] |
| 467.58(12) | 7.1(1) | 467.58(12) | 0 | −0.11(4) | 501 879 |
| 501.28(12) | 7.6(3) | 1847.38(16) | 1346.10 | −0.22(3) | (164 188)[c] 379 468 879 967 |
| 878.83(21) | · · · | 1346.10(11) | 467.58 | d | |
| 966.62(02) | 10.0(2) | 1346.10(11) | 379.42 | −0.22(4) | (164)[c] 379 501 |
| 1015.63(25) | 8.8(1)[e] | 1395.05(27) | 379.42 | e | 379 |

[a]Relative gamma-ray intensities in the continuous beam data.
[b]Coefficient in the Legendre polynomial expansion $W(\theta)=I_\gamma[1+A_2P_2(\cos\theta)]$ of the gamma-ray angular distribution measured at $E_t=16$ MeV.
[c]These gamma rays are not prominent in the pulse-height distribution.
[d]No angular distribution measured due to weak intensity in the singles spectrum.
[e]This gamma ray was part of an unresolved doublet in the singles spectrum. No angular distribution or intensity was measured for the $^{205}$Hg component.

cleus because of the agreement of these energies with the first two excited states observed in the (d,p) study. Other gamma rays could then be assigned to the (t,d) channel by the coincidence data. In addition, we checked that none of the gamma rays in Table I were coincident with any transitions from the other reaction channels, particularly the dominating $^{204}$Hg(t,2n)$^{205}$Tl channel. Coincidence relations are also listed in Table I, and Fig. 1 shows examples of the coincidence spectra. The experiment with the deflected beam showed that the strong gamma rays with energies of 379, 967, and 1016 keV are delayed with $\tau_m=(1.59\pm0.06)\times10^{-3}$ s.

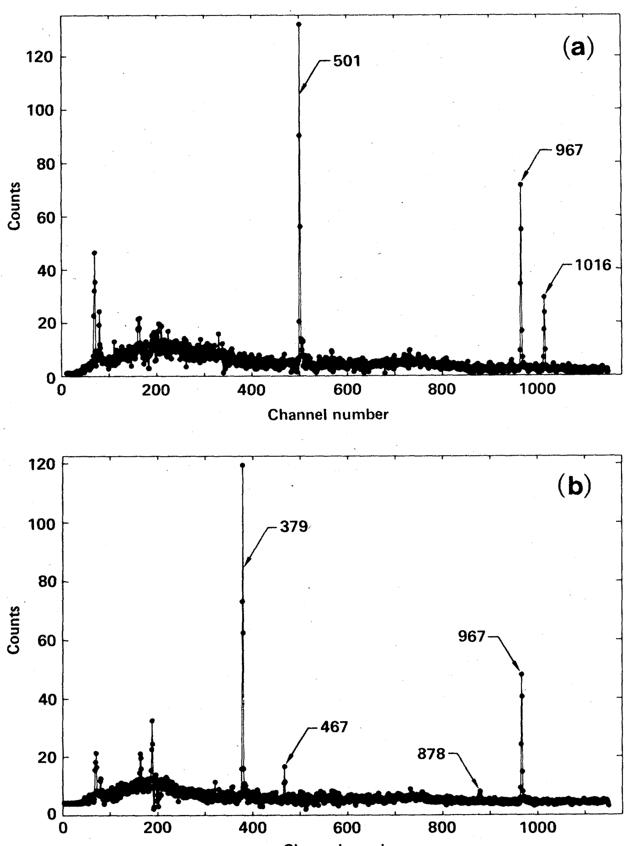


FIG. 1. Spectra in coincidence with (a) the 379-keV and (b) 501-keV transitions from the reactions of 16-MeV tritons with $^{204}$Hg.

Our proposed partial level scheme for $^{205}$Hg is illustrated in Fig. 2. In forming this level scheme we were aided by the results of the (d,p) study of Moyer shown in Fig. 2(a). We can assign the 501- and 967-keV gamma rays, which are coincident with the 379-keV transition, as the cascade decay of the 1847-keV state. The spectrum in coincidence with the 501-keV gamma ray is consistent with this assignment and also identifies the 879- and 468-keV transitions as an alternate branch for the decay of the level at 1346 keV. The branching ratio (B.R.) for the 1346-keV level can be estimated from the coincidence spectra after correcting for detector efficiency. The results are, in percent, B.R.(1346 → 379) = 94(1) and B.R.(1346 → 468) = 6(1).

As noted earlier, the search for time delayed gamma rays showed that three gamma rays with energies of 379, 967, and 1016 keV all exhibited a mean life $\tau_m=1.59\times10^{-3}$ s. All three of these gamma rays had prompt components in their time distributions, which means that none of them directly depolpulates the isomeric level. We postulate that the 1016-keV transition represents the decay of a level at 1395 keV (1395 → 379), and that this level is fed by an unobserved transition from the isomeric state. Furthermore, we propose that the 1395-keV level has an unobserved branch to the 1346-keV level, thus accounting for the delayed component of the 967-keV gamma ray. In the delayed spectrum the intensity ratio $I(1016)/I(967+879)=4.2(3)$ gives the branching ratios (in percent) of B.R.(1395 → 1346) = 19(1) and B.R.(1395 → 379) = 81(1).

In the delayed spectrum there were several other weak gamma rays, all but one of which could be explained by the 0.26% of $^{200}$Hg impurity in the $^{204}$Hg target. Gamma-ray peaks of 331 and 588 keV had measurable half-lives of 2.0 ± 0.6 ms, in good agreement with decay of the 2.1-ms isomer at 919.6 keV in $^{201}$Tl. Two other weaker gamma rays have energies of 460 and 490 keV that agree well with the decay of the 0.57-ms isomer at 950.2 keV in $^{202}$Tl. The half-life exhibited by the 490-keV gamma ray was 0.5 ms

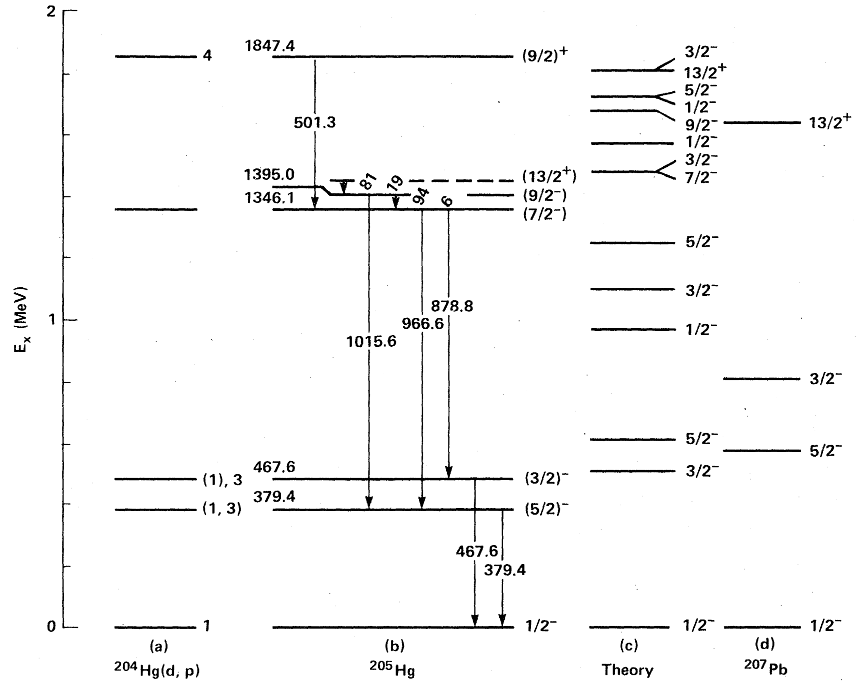


FIG. 2. The experimental level scheme of $^{205}$Hg in comparison with (a) the results of the reaction $^{204}$Hg(d,p)$^{205}$Hg, (c) a shell model calculation using the Kuo-Herling interaction (Ref. 1), and (d) experimental results for $^{207}$Pb. The proposed spin-parity assignments for states in $^{205}$Hg are discussed in the text. In (a) we show the $l$-transfer values reported in the (d,p) reaction, and in (b) energies are in keV and gamma-ray branching ratios in percent.

with an estimated error of 50%. We could not determine the origin of a peak at 563 keV, whose half-life, measured as 1.4 ms, is only marginally compatible with the $^{205}$Hg$^m$ half-life of 1.10 ms.

Our proposed level scheme accounts for all the strong lines in the coincidence spectra except for the 164- and 188-keV gamma rays, which are in prompt coincidence with the 379-keV and 501-keV transitions. These lines cannot be placed among the known energy levels.

Plausible spin and parity assignments can be made for these levels in $^{205}$Hg by combining our gamma-ray data with the results of Moyer and the systematics of this mass region. Using the systematics, we propose that the origin of the isomer is the $i_{13/2}$ neutron hole state. The isomeric decay is via an $M2$ transition to the $\frac{9}{2}^-$ state with configuration $\nu(f_{5/2})^{-1}(\pi^{-2})_{2^+}$. Blomqvist[9] estimates an energy of 1.8(2) MeV for the $\nu(i_{13/2})^{-1}$ state and an energy of 1.4 MeV for the $\frac{9}{2}^-$ state. This suggests an energy of $\approx$400 keV for the isomeric transition, but the actual energy must be considerably smaller, since we could not detect the isomeric gamma rays. We can estimate the energy of the isomeric transition by using data from the decay of $\nu(i_{13/2})^{-1}$ isomers in the lighter mercury isotopes. These nuclei have been studied by Günther *et al.*,[10] and based upon their work we estimate $B(M2)=0.28\ \mu^2\ \mathrm{fm}^2$. Using this value we find that the quantity $E_\gamma^5$ (MeV) $(1+\alpha_T)=1.6\times10^{-4}$, and therefore $E_\gamma=55$ keV. This energy is too low to have been detectable in our experiments. Because of the large internal conversion coefficient, the threshold below which we would not be able to detect an $M2$ transition in any of our gamma-ray experiments was of the order of 150 to 200 keV. $K$ and $L$ x-ray intensities could not be determined from our data with sufficient accuracy to shed any light on the $M2$ transition energy.

Based on the arguments given above, we propose $J^\pi=\frac{9}{2}^-$ for the level at 1395 keV. The dominant decay mode of this state is 1395 $(J^\pi=\frac{9}{2}^-)\rightarrow 379(J^-)\rightarrow 0$ $(J^\pi=\frac{1}{2}^-)$. Based upon the lifetime limit $\tau_m<10$ ns for these levels and on the angular distributions of the gamma rays, we assign $J^\pi=\frac{5}{2}^-$ for the 379-keV level. The spin of the 1346-keV level can be inferred from the properties of the gamma-ray transitions using $J^\pi$ $(1847)=\frac{9}{2}^+$, as suggested by the (d,p) data. The gamma rays in the cascade 1847 $(J^\pi=\frac{9}{2}^+)\rightarrow 1346(J^\pi)\rightarrow 379$ $(J^\pi=\frac{5}{2}^-)$ have similar angular distributions that favor $\Delta J=1$ for both transitions. Therefore, we assign $J=\frac{7}{2}$ for the level at 1346 keV. The experimental data are not as definitive in determining the parity for this state. However, the branching ratios from both the 1395- and the 1346-keV levels favor negative parity for the 1346-keV state. With negative parity, the $1395\rightarrow1346$ branch that competes favorably with the $1395\rightarrow379$ $E2$ transition is $M1$, and the weaker 879-keV branch seen in the decay of the 1346-keV level is $E2$ in competition with $M1$, instead of $M2$ in competition with $E1$. Shell model calculations also support this assignment, since they predict negative parity states at this excitation energy.

The level scheme constructed from the gamma transitions agrees well with that from the (d,p) measurement (Fig. 2). The 1847-keV level is strongly excited in the $^{204}$Hg(d,p) reaction. It is also prominent in our data, which suggests that it is populated by the analogous direct (t,d) reaction.

The $\frac{13}{2}^+$ isomeric state, on the other hand, was not observed in the (d,p) study, in agreement with its proposed neutron-hole structure. Figure 2(d) shows the levels of $^{207}$Pb (Ref. 11) for comparison. These states correspond to the single neutron holes $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, and $i_{13/2}$. Corresponding levels are seen in our proposed $^{205}$Hg scheme, with energies lowered by 200 to 300 keV, due to the presence of the two proton holes in $^{205}$Hg. Also the $\nu g_{9/2}$ level that intrudes from the next higher shell is lowered by nearly 1 MeV from $E_x = 2.73$ MeV in $^{207}$Pb to $E_x = 1.85$ MeV in $^{205}$Hg.

Silvestre-Brac and Boisson performed a shell-model calculation with the Kuo-Herling interaction for the three-hole states of $^{205}$Hg. The results up to the $\frac{13}{2}^+ - \frac{3}{2}^-$ doublet near $E_x = 1800$ keV are shown in Fig. 2(c), and they reproduce the experimental energy levels within 300 keV. Our experimental level at 1847.5 keV is probably of 1p-4h structure, and therefore should not be compared with the calculated $\frac{9}{2}^+$ state at 2277 keV [not shown in Fig. 2(c)]. Tabulated wave functions are not presented, and, therefore, we cannot compare theoretical predictions with the measured branching ratios. However, their results do suggest that the low-lying levels that we observe can be described as a neutron hole in $^{206}$Hg.

We thank C. Günther, Bonn, for informing us about his results on other Hg isotopes, and both C. Günther and J. Blomqvist, Stockholm, for very helpful discussions. This work was performed under the auspices of the U.S. Department of Energy by the Lawerence Livermore National Laboratory under Contract No. W-7405-ENG-48, and under Contract No. PHY82-05952 between the National Science Foundation and the Florida State University.

---

*Present address: Lawrence Livermore National Laboratory, Livermore, CA 94550.

†Present address: A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06511.

[1] B. Silvestre-Brac and J. P. Boisson, Phys. Rev. C **24**, 717 (1981).

[2] R. A. Moyer, Phys. Rev. C **5**, 1678 (1972).

[3] M. R. Schmorak, Nucl. Data Sheets **23**, 287 (1978).

[4] K. H. Maier, T. Nail, R. K. Sheline, W. Stöffl, J. A. Becker, J. B. Carlson, R. G. Lanier, L. G. Mann, G. L. Struble, J. A. Cizewski, and B. H. Erkkila, Phys. Rev. C **27**, 1431 (1983).

[5] J. A. Becker, J. B. Carlson, R. G. Lainer, K. H. Maier, L. G. Mann, G. L. Struble, T. W. Nail, R. K. Sheline, W. Stöffl, L. E. Ussery, J. A. Cizewski, and B. Erkkila, Nucl. Instrum. Methods **211**, 379 (1983).

[6] J. A. Becker, J. B. Carlson, R. G. Lanier, L. G. Mann, G. L. Struble, K. H. Maier, L. E. Ussery, W. Stöffl, T. Nail, R. K. Sheline, and J. A. Cizewski, Phys. Rev. C **26**, 914 (1982).

[7] K. H. Maier, J. A. Becker, J. B. Carlson, R. G. Lanier, L. G. Mann, G. L. Struble, T. Nail, R. K. Sheline, W. Stöffl, and L. Ussery, Phys. Rev. Lett. **48**, 466 (1982).

[8] J. A. Becker, R. G. Lanier, L. G. Mann, G. L. Struble, K. H. Maier, L. E. Ussery, W. Stöffl, T. W. Nail, R. K. Sheline, J. A. Cizewski, B. H. Erkkila, and J. Blomqvist, Phys. Rev. C **29**, 1268 (1984).

[9] J. Blomqvist (private communication).

[10] C. Günther *et al.* (private communication).

[11] *Table of Isotopes*, 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).