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PHYSICAL REVIEW C VOLUME 6, NUMBER 4 OCTOBER 1972

New High-Spin Isomer 2.3-Day ^{198m}Au and the ^{198}Au Level Structure*

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In 18-MeV deuteron bombardments of enriched ^{200}Hg, we have produced a new isomer 2.27 ± 0.05-day ^{198m}Au, which is believed to be analogous to the $(h_{11/2}\pi, i_{13/2}\nu)12^-$ isomer in ^{196}Au. No β^- branching is observed in the decay of ^{198m}Au. The isomeric transition is followed by a cascade of 204.10- and 180.31-keV γ rays to a 123-nsec level at 312.10 keV which deexcites to ground by a sequence of 97.21-keV ($E1$) and 214.89-keV ($E2$) transitions. A revised interpretation of the results of earlier (n, γ) and $(d, p\gamma)$ studies of the ^{198}Au level structure is presented and shell-model assignments for the levels populated in the isomeric decay are proposed. It is argued that the $E1$ deexcitation of the 123-nsec isomer involves the l-forbidden single-particle transition $(d_{3/2}\pi, i_{13/2}\nu)5^+ \rightarrow (d_{3/2}\pi, f_{5/2}\nu)4^-$.

I. INTRODUCTION

Most of the information now available on the ^{198}Au level structure has been obtained in extensive neutron-capture γ-ray studies.[1-3] The level spectrum, including a negative-parity first excited state at 55.2 keV, has been established mainly on the basis of energy sums and transition intensities.[4] A 123-nsec isomer, deexciting by a sequence of 97.2-keV ($E1$) and 214.9-keV ($E2$) transitions, has been studied in ^{197}Au$(d, p\gamma)$ by Bonitz[5] and in ^{197}Au(n, γ) by Löbner *et al.*[6] Since the latter workers obtained some indication that the isomer deexcites through the 55.2-keV level, they placed the 123-nsec level at 367.3 keV, thereby accommodating a known primary capture γ ray; J^π values of 1^+ or 3^+ were inferred.

In ^{196}Au, a 12^- isomer, arising from the coupling of an $h_{11/2}$ proton and an $i_{13/2}$ neutron, has been known for several years.[7-10] More recently, we discovered a 19-h isomer in ^{200}Au, which decays predominantly by β^- emission to high-spin levels in ^{200}Hg[11]; very recent NMR measurements with oriented ^{200m}Au nuclei have shown that this isomer is analogous to the 12^- isomer in ^{196}Au.[12] In the course of a more detailed investigation of the ^{200m}Au decay using a gold source produced in 18-MeV deuteron bombardments of enriched ^{202}Hg, we observed 97.2- and 214.9-keV γ rays decaying with a half-life of about 50 h. Since these radiations did not correspond to those of any known gold activity, further experiments were planned to establish the correct mass assignment and to determine the decay properties more completely.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Source Preparation, Mass Assignment, and Half-Life

Target materials consisted of the enriched mercury isotopes ^{200}Hg (88.9%), ^{202}Hg (76.8%), and ^{204}Hg (68.6%) in the form of HgS. Samples weighing 10–15 mg were wrapped in high-purity aluminum foil and bombarded with 18-MeV deuterons in the water-cooled target holder of the Argonne National Laboratory 60-in. cyclotron. The integrated beam intensity was about 8 μA h.

Chemical separation of gold activities from the irradiated samples was begun about 3 h after bombardment. The HgS was dissolved in *aqua regia* and Au (150 μg), Na, and Tl carriers were added. The gold activities were separated by standard radiochemical procedures which involved solvent extraction from 6 *M* HCl into ethyl acetate and coprecipitation of gold with tellurium metal. In the preparation of a source for conversion-electron measurements, the tellurium was removed by cation exchange and the gold was electrodeposited on a nickel backing foil.

Subsequent γ-ray measurements showed clearly that the intensities of the 97.2- and 214.9-keV γ rays were directly proportional to the ^{200}Hg abundances in the target materials; the relative intensities of the 412-keV γ ray (from ^{198g}Au decay) and the 97- and 215-keV γ rays did not vary with target composition. The new activity was therefore assigned to ^{198m}Au and the half-life was determined by following the decay of the two strong γ rays over a period of about a week. The result $T_{1/2}$

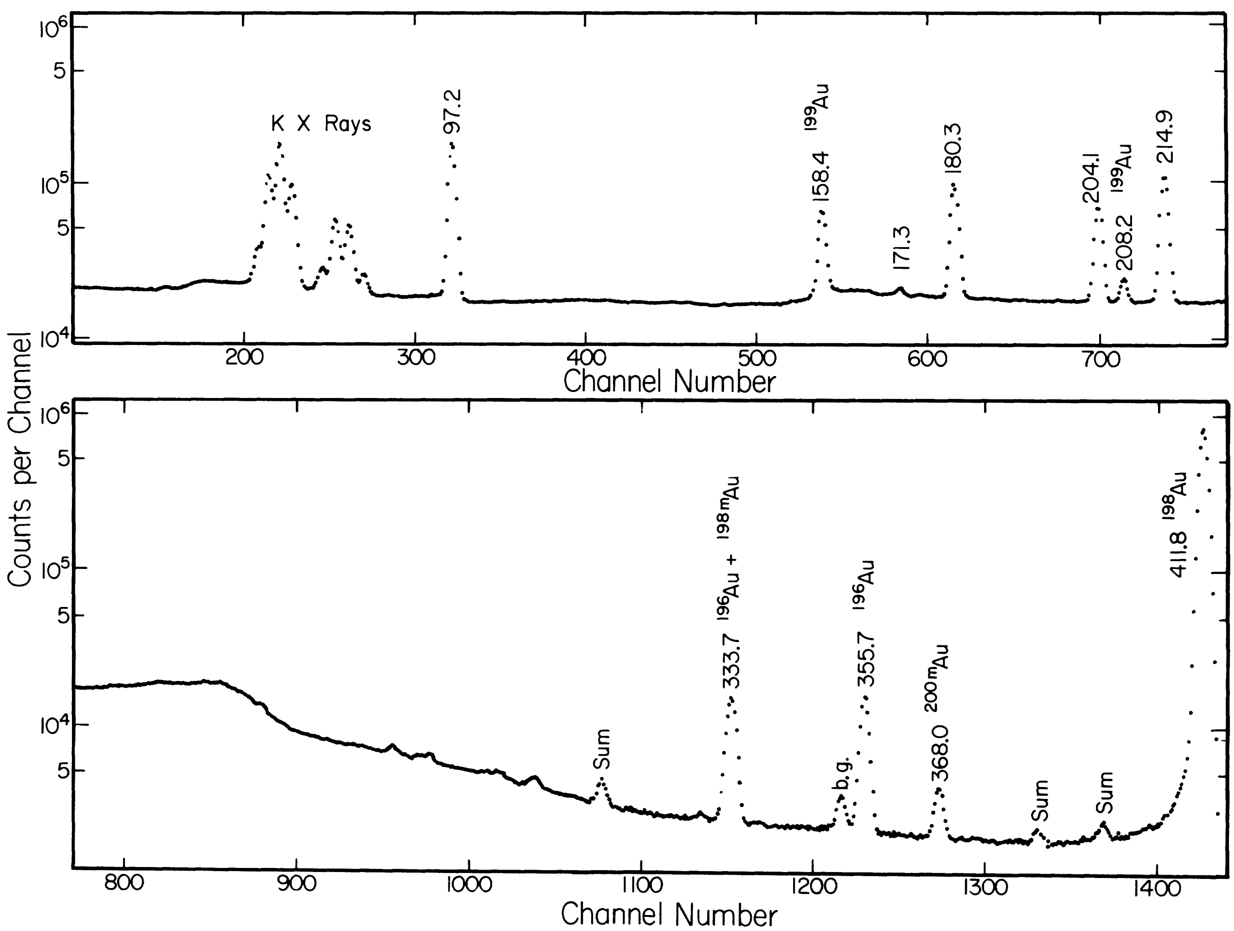

FIG. 1. The γ-ray spectrum of 2.3-day ^{198}Au.

= 2.27 ± 0.05 days was obtained.

Isomer ratio measurements for the production of ^{196m}Au/^{196g}Au, ^{198m}Au/^{198g}Au, and ^{200m}Au/^{200g}Au in the deuteron bombardments showed that, in all three cases, about 7% of the total (d, α) reaction cross section leads to population of the high-spin isomer. This result lends support to the view that ^{198m}Au, like ^{196m}Au and ^{200m}Au, has a spin-parity of 12^-. The relatively large yields of the high-spin isomers are probably a consequence of the momentum mismatch inherent in the (d, α) reaction, since this gives rise to sizable high l-transfer contributions to the cross section.

B. γ-Ray Measurements

Singles γ-ray measurements were performed using a 40-cm^3 Ge(Li) detector in conjunction with a 4096-channel analyzer. The system energy resolution was 2.1 keV full width at half maximum (FWHM) for the 1332-keV γ rays of ^{60}Co. Since the activity of interest was rather weak, it was necessary to place the source within 5 cm of the detector to obtain high-quality γ-ray spectra. At this distance, some coincidence summing occurs in the detector, but measurements were also performed with the source at greater distances from the detector so that sum peaks could be identified.

A γ-ray spectrum of the Au source prepared from the enriched ^{200}Hg target is shown in Fig. 1. An analysis of sequential γ-ray spectra taken over a period of six days showed that the four strong γ rays, 97.21, 180.31, 204.10, and 214.89 keV, occur in the decay of ^{198m}Au. In addition, the broad photopeak at ~333.7 keV was resolved into a strong 333.8-keV component from 2.3-day ^{198m}Au decay and a weaker 333.0-keV component from 6.2-day ^{196}Au. A 171.3-keV γ ray may also occur in the ^{198m}Au decay, but it was not possible to determine an accurate half-life for this very weak line; in any case it represents not more than a few percent of the decay intensity. The precision of the γ-ray energy determinations and the coincidence results described below leave little doubt that the 97.21- and 214.89-keV transitions seen in the ^{198m}Au decay are identical with the transitions of the same energies identified in the (n,γ) and (d,p) studies. Therefore, a particularly careful search was made for a 55.2-keV γ ray but it was unsuccessful: The maximum possible intensity of such a γ ray is less than 1% of the 97.2-keV γ-ray intensity. Since the total conversion coefficient for the 55.2-keV transition is known[4] to be about 16, the present results rule out the possibility that the 97-, 215-keV γ-ray cascade populates the 55-keV level. An unsuccessful search was also made for a 636.7-keV γ ray corresponding to the known $4^+ \to 2^+$ transition in ^{198}Hg. It is concluded that there is no evidence for a β^- branch in the ^{198m}Au decay corresponding to the strong β^- branch in the decay of ^{200m}Au. The energies and relative intensities of the γ rays assigned to ^{198m}Au decay

TABLE I. Transitions observed in the decay of 2.3-day ^{198m}Au.

E_γ (keV)	Relative γ-ray intensity	Multipolarity	Relative transition intensity
97.21 ± 0.05	91 ± 4	$E1$	130 ± 6
180.31 ± 0.05	66 ± 5	($E2$)	99 ± 8
204.10 ± 0.06	54 ± 4	($M1$)	100 ± 7
214.89 ± 0.05	100	$E2$	127
333.82 ± 0.15	20 ± 5		

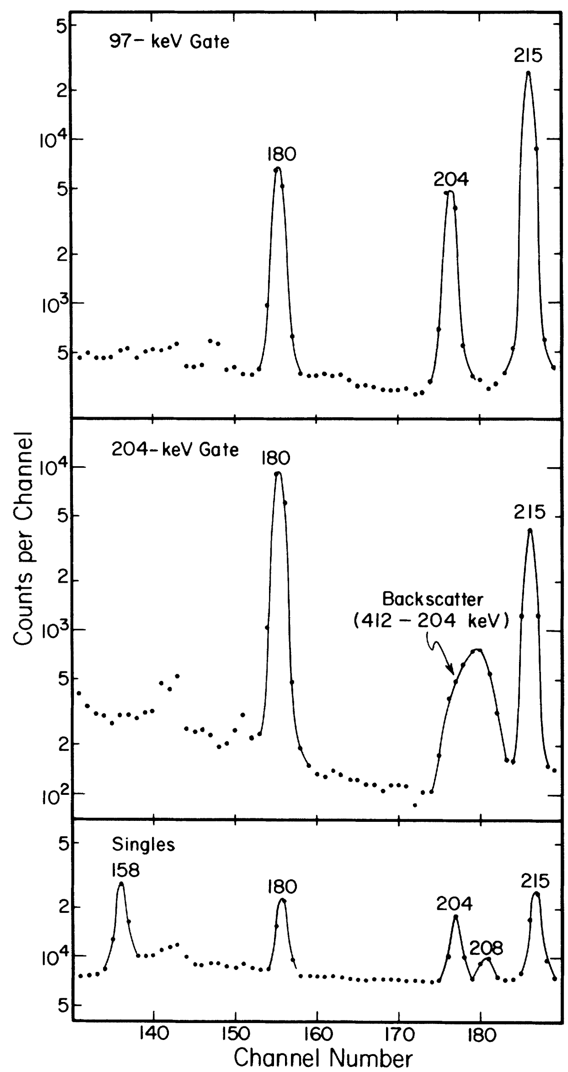

FIG. 2. Typical γ-γ coincidence spectra obtained with a resolving time $2\tau = 90$ nsec.

are listed in Table I.

γ-γ coincidence experiments were also performed using two Ge(Li) detectors. It was found that the 180- and 204-keV γ rays are in prompt coincidence and that both transitions are in delayed coincidence with the 97- and 215-keV transitions deexciting the 123-nsec level. The 334 transition is not coincident with the 180- and 204-keV γ rays but occurs in a weaker decay branch into the 123-nsec level. Some typical γ-γ coincidence data are illustrated in Fig. 2. The order of the 180.31- and 204.10-keV transitions remains uncertain. The fact that the list of transitions observed in the (n,γ) measurements includes a weak 204.07-keV γ ray but no 180.31-keV γ ray suggests that the 180-keV transition may precede the 204-keV transition.

An attempt was made to identify the isomeric transition by measuring the electron spectrum with a cooled Si(Li) spectrometer. However, we were unable to detect the ^{198m}Au conversion lines, partly because the activity available was weak, but more particularly because the electron spectra obtained were dominated by the intense β^- continuum from ^{198g}Au, which has a similar half-life.

III. ^{198}Au LEVEL SCHEME

The combined data from the present work and from the (n,γ) studies indicate that the 123-nsec lifetime must be associated with a positive-parity level at 312 keV which deexcites by an $E1$ transition to a negative-parity level at 215 keV; the proposed J^π values of 5^+ and 4^-, respectively, are consistent with the fact that neither level is populated by a primary capture γ ray. The multipolarities of the 180- and 204-keV transitions have not been experimentally determined, but intensity-balance requirements suggest rather strongly that they have $E2$ and $M1$ character, respectively. When these multipolarities are assumed, the transition intensities shown in Table I are obtained. Not only are the intensities of the 180- and 204-keV transitions closely equal, but a satisfactory intensity balance is achieved at the 312-keV level, regardless of the choice of $E2$, $M1$, or $E1$ multipolarity for the weaker 334-keV transition.

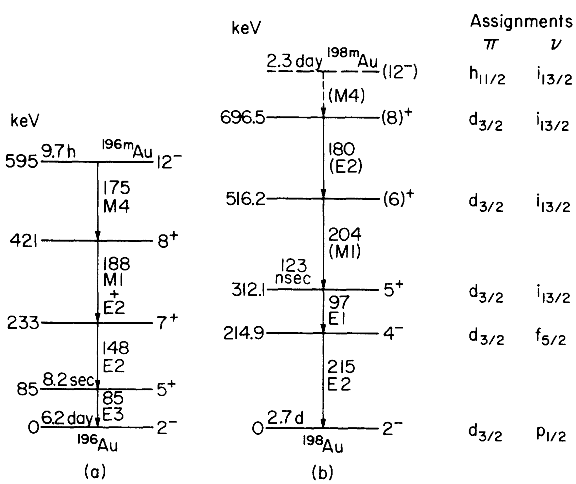

FIG. 3. (a) The ^{196m}Au decay scheme (see Refs. 9 and 13); (b) The proposed ^{198m}Au decay scheme.

Further insight into the nature of the ^{198}Au levels can be obtained by considering the main deexcitation path in the ^{196m}Au decay[9,13] [Fig. 3(a)]. An interpretation of the ^{196}Au levels in terms of the shell model has been proposed by Wapstra *et al.*[9] who assigned the observed 5^+, 7^+, and 8^+ levels to the configuration $(d_{3/2}\pi, i_{13/2}\nu)$, in which case the 12^- isomer deexcites by a $h_{11/2}\pi \to d_{3/2}\pi$ $M4$ transition. It is likely that the ^{198}Au isomer deexcites in a similar fashion and the proposed partial decay scheme is shown in Fig. 3(b), together with shell-model assignments for the levels which are consistent with all the observations. As mentioned earlier, the order of the transitions in the 180–204-keV γ-ray cascade between the 696.5- and 312.1-keV levels has not been firmly established. If the transition order were reversed, the intermediate level would lie at 492.4 keV with probable J^π values of 7^+, and the ^{198}Au level structure would more closely resemble that of ^{196}Au. However, in view of the (n,γ) data, the order shown in Fig. 3(b) is slightly favored.

A 4^- level with the probable configuration $(d_{3/2}\pi, f_{5/2}\nu)$ is known in several odd-odd Tl isotopes and the present results suggest that a similar excitation occurs at 214.9 keV in ^{198}Au. The 97-keV $E1$ transition is retarded by a factor of 10^6 with respect to the Weisskopf estimate; this high degree of hindrance is almost certainly due to the l-forbidden nature of the $(d_{3/2}\pi, i_{13/2}\nu)5^+ \to (d_{3/2}\pi, f_{5/2}\nu)4^-$ single-particle transition. It would seem that high-resolution studies of the ^{197}Au$(d,p)^{198}$Au reaction and a more detailed examination of the population of the 214.9- and 312.1-keV levels following neutron capture in ^{197}Au could further increase our understanding of the ^{198}Au level structure.

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Levels of ^{155,157,159,161}Tb Excited in Helium-Induced Single-Proton-Transfer Reactions*

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Energy levels of ^{155,157,159,161}Tb have been studied through the (^{3}He,d) and (α,t) reactions on ^{154,156,158,160}Gd, run with 25.5-MeV ^{3}He and 27.0-MeV α particles, respectively. Distorted-wave Born-approximation analysis was used to interpret the reaction results, with transferred l values obtained from the comparison of the experimental and theoretical values of the cross-section ratio, $R = d\sigma(^3\mathrm{He},d)/d\sigma(\alpha,t)$. The spectroscopic information obtained was compared to the theoretical predictions of the Nilsson model. Corrective terms added included the Coriolis and pairing interactions. Many of the levels excited were identified as members of rotational bands built on Nilsson single-particle configurations. Identified in all four nuclei are the [411↑], [413↓], [532↑], [404↓], [402↑], and [411↓] Nilsson configurations. Other bands identified are the [541↓] in ^{157,159,161}Tb, the [523↑] in ^{159,161}Tb, the [411↑] γ mixed configuration in ^{155,157,159}Tb, and the [514↑] configuration in ^{155}Tb.

I. INTRODUCTION

Single-nucleon-transfer reactions have proved to be a sensitive means of probing nuclear structure. These reactions ordinarily complement nuclear structure studies performed by following radioactive decay, or by inducing Coulomb excitation.

Satchler[1] has pointed out the usefulness of these reactions in the study of deformed nuclei, where the splitting of strength among the members of a rotational band is dependent on the structure of the intrinsic state. This makes the single-nucleon-transfer reaction suitable for the identification of configurations whose structure is approximated by the Nilsson model.

Proton-transfer reactions on deformed nuclei are few in number, due in large part to the experimental difficulties inherent in a (d,n) reaction and to the previous lack of suitable beams of ^{3}He, ^{4}He, or heavier ions. Recently with the advent of higher-energy accelerators, high-resolution spectrographs, and sizable beams of negative He ions, He-induced proton-transfer reactions have become experimentally feasible, even in the actinide region.[2]

This paper is concerned with an investigation of the levels of ^{155,157,159,161}Tb by (^{3}He,d) and (α,t) reactions. The stable Gd targets used for these proton-transfer reactions start at the edge of the deformed region, $N=90$. We studied Tb nuclei with neutron numbers $N=90,92,94,96$, which gave us the opportunity to observe the levels occupied by the 65th proton as deformation changed quickly.

The (α,t) reaction, by virtue of the fact that it involves breakup of the α particle favors higher momentum transfer than the (^{3}He,d) reaction. The ratio $R = d\sigma(^3\mathrm{He},d)/d\sigma(\alpha,t)$ is a sensitive measure of the momentum transfer so that l values are obtained without the use of angular distributions.

The low-lying levels of these nuclei have been