PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 28, NUMBER 6 DECEMBER 1983

# $^{197}$Au(t,p)$^{199}$Au reaction

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(Received 31 May 1983)

The level structure of $^{199}$Au was investigated via the $^{197}$Au(t,p) reaction induced with a 17 MeV triton beam. Essentially all of the $L=0$ transfer strength is observed in the ground state transition. The distribution of $L=4$ transfer strength follows the systematic behavior observed previously in the Pt(t,p) reactions.

[NUCLEAR REACTIONS $^{197}$Au(t,p), $E=17$ MeV; measured energy levels, $\sigma(\theta)$ in $^{199}$Au; distorted wave Born approximation calculations.]

## I. INTRODUCTION

The study of two-neutron transfer reactions on odd-$A$ medium- and heavy-mass nuclei has frequently been a more sensitive probe of the transitional character of the structure in a region than has such study on even-even targets. The Os-Pt-Hg region has long been known to be of transitional character, with structure intermediate between well-deformed prolate shape, characteristic of rare-earth nuclei, and spherical shell model structure, characteristic of the Pb nuclei. Two-neutron transfer studies on the even-even nuclei[1-3] have shown a very smooth trend, with

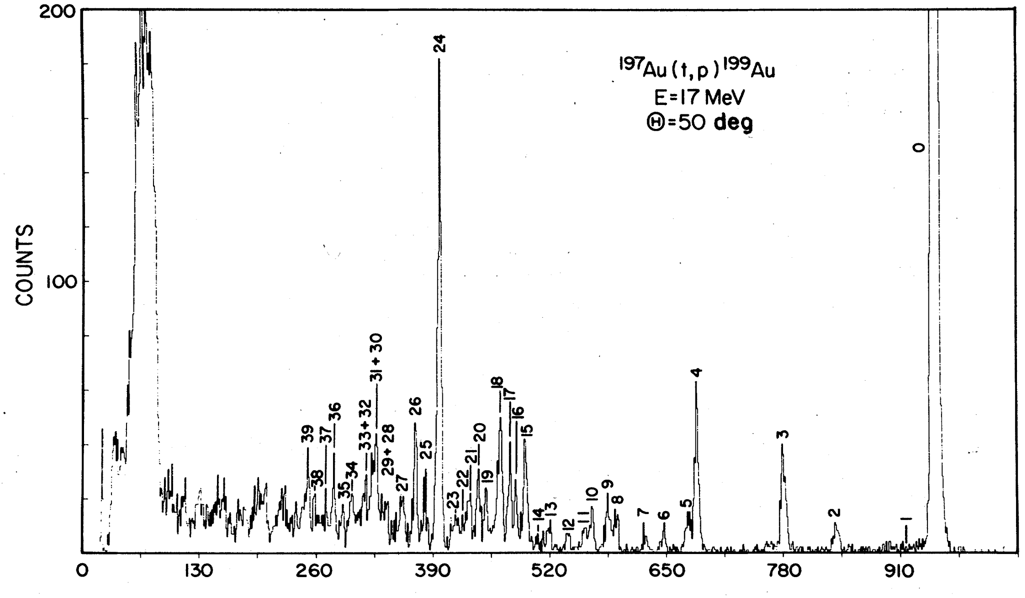

FIG. 1. Spectrum of the $^{197}$Au(t,p)$^{199}$Au reaction at 50° obtained with 17 MeV tritons. The peaks are labeled by the level numbers in Table I.

TABLE I. Results from the $^{197}$Au(t,p)$^{199}$Au measurements.

| | Present results[a] | | | | Earlier results[b] | |
|---|---|---|---|---|---|---|
| Level no. | $E_x$ (keV) | $\frac{d\sigma}{d\Omega}(50°)$ ($\mu$b/sr) | $L$ | $J^\pi$ | $E_x$ (keV) | $J^\pi$ |
| 0 | 0 | 154(2) | 0 | $\frac{3}{2}^+$ | 0 | $\frac{3}{2}^+$ |
| 1 | 78 | 0.4(2) | | | 77.20 | $(\frac{1}{2})^+$ |
| 2 | 325 | 1.2(2) | | | 317.07<br>323.60 | $(\frac{5}{2})^+$<br>$(\frac{3}{2})^+$ |
| 3 | 498 | 4.7(5) | 2 | | 493.75 | $(\frac{7}{2})^+$ |
| 4 | 791 | 6.1(5) | 0 | $\frac{3}{2}^+$ | 791.74 | $(\frac{3}{2})^+$ |
| | | | | | 820. | $(\frac{1}{2}^+)$ |
| 5 | 822 | 1.4(3) | 2 | | 822.5 | $(\frac{7}{2})^+$ |
| 6 | 905 | 0.8(2) | 0 | $\frac{3}{2}^+$ | | |
| 7 | 968 | 0.6(2) | 2 | | 968.32 | $(\frac{3}{2},\frac{5}{2}^+)$ |
| 8 | 1070 | 1.7(3) | 2 | | 1069.9 | $(\frac{3}{2}^+)$ |
| 9 | 1102 | 2.0(3) | (2) | | 1104.0 | $(\frac{5}{2}^+)$ |
| 10 | 1158 | 1.7(2) | (2) | | 1159.0 | |
| 11 | 1185 | 0.9(2) | 2 | | 1194. | |
| 12 | 1244 | 0.9(2) | 2 | | 1249.4 | |
| 13 | 1312 | 0.8(3) | | | | |
| 14 | 1344 | 0.4(3) | | | 1340. | |
| 15 | 1396 | 4.5(5) | 4 | | 1396.6 | $(\frac{5}{2}^+)$ |
| 16 | 1432 | 2.2(4) | | | | |
| 17 | 1454 | 3.0(4) | 4 | | | |
| 18 | 1489 | 5.8(5) | 4 | | | |
| 19 | 1539 | 2.6(4) | | | | |
| 20 | 1568 | 3.0(4) | 4 | | | |
| 21 | 1602 | 2.7(4) | 4 | | | |
| 22 | 1635 | 1.0(3) | | | | |
| 23 | 1660(7) | 1.3(3) | | | | |
| 24 | 1709 | 16(1) | 4 | | | |
| 25 | 1765 | 2.5(5) | 4 | | 1770. | $(\frac{7}{2}^-)$ |
| 26 | 1801 | 4.5(6) | 0 | $\frac{3}{2}^+$ | | |
| 27 | 1849 | 2.6(5) | | | | |
| 28 | 1908 | 1.9(4) | | | 1910. | $(\frac{9}{2}^-)$ |
| 29 | 1926 | 1.0(4) | | | | |
| 30 | 1948 | 4.5(5) | 2 | | | |
| 31 | 1967 | 2.1(4) | | | | |
| 32 | 1994[c] | 2.7(5) | | | | |
| 33 | 2008(7) | 1.1(4) | | | | |
| 34 | 2038 | 2.4(5) | | | | |
| 35 | 2073 | 1.2(3) | | | | |
| 36 | 2107 | 2.2(4) | | | | |
| 37 | 2139 | 1.5(4) | | | | |
| 38 | 2174 | 1.5(4) | | | | |
| 39 | 2205 | 2.4(4) | | | | |

[a] Excitation energies in keV, cross sections at 50° in $\mu$b/sr, and angular momentum assignments from the present measurement. Errors in parentheses are on the last digit and are statistical. Excitation energy errors are 5 keV unless otherwise noted.

[b] Results for $^{199}$Au as compiled in Ref. 5.

[c] Definitely two separate states at approximately 1994 and 2008 keV.

the $L=0$ strength concentrated in the ground-state to ground-state transitions. However, the observation of considerable fragmentation of the $L=0$ strength in the $^{195}$Pt(t,p)$^{197}$Pt reaction[4] prompted a study of the two-neutron transfer reactions on odd-mass targets in the $A=190$ transitional region. The current investigation of the (t,p) reaction on $^{197}$Au is a part of this survey.

The $^{199}$Au nucleus has been quite extensively studied[5] via $\beta$ decay and (n,$\gamma$) and charged-particle transfer reactions. However, relatively few firm $J^\pi$ values have been assigned to its excited states. In addition to enabling additional spectroscopic information to be obtained, the present (t,p) study can also be of value in restricting $J^\pi$ assignments in $^{199}$Au because of the characteristic shape of the $L=0$ angular distributions.

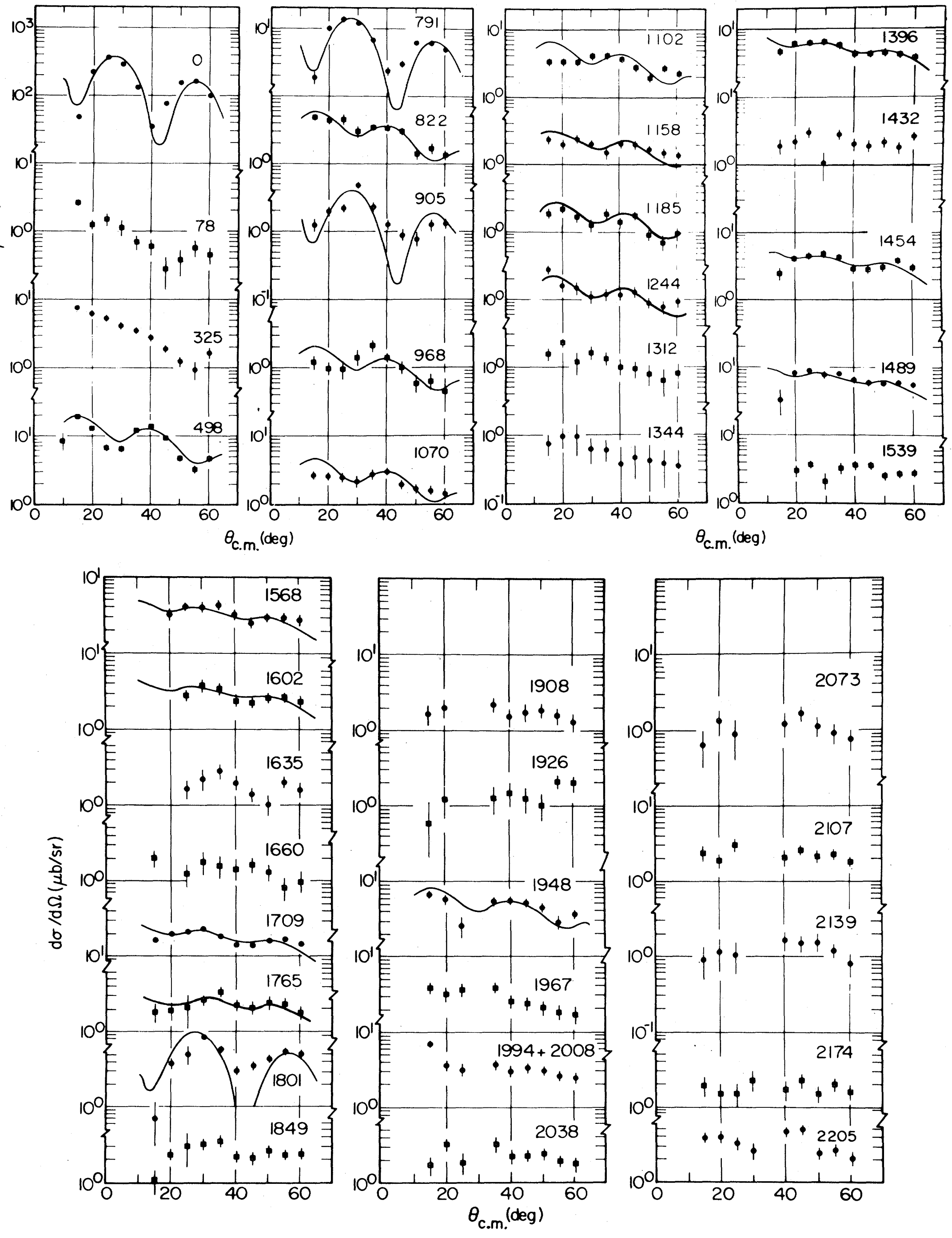

FIG. 2. Angular distributions for the transitions populating the indicated states in $^{199}$Au. The data of the residual states are labeled by the excitation energies (in keV). The solid curves are DWBA calculations for assumed $L=0$, $L=2$, and $L=4$ transitions.

TABLE II. Optical model parameters used in distorted wave calculations.

| Particle | $V$ (MeV) | $r_r$ (fm) | $a_r$ (fm) | $W$ (MeV) | $W_D$ (MeV) | $r_w$ (fm) | $a$ (fm) | $V_{so}$ (MeV) | $r_{so}$ (fm) | $a_{so}$ (fm) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| t | 166.7 | 1.16 | 0.752 | 10.5 | 0 | 1.498 | 0.817 | | | | 9 |
| p | 51.0 | 1.25 | 0.650 | 0. | 13.5 | 1.25 | 0.47 | 7.5 | 1.25 | 0.47 | 10 |

## II. EXPERIMENTAL PROCEDURES

The $^{197}$Au(t,p) reaction was measured at the Los Alamos National Laboratory Tandem Van de Graaff facility with a 155 $\mu$g/cm$^2$ gold foil. A beam of 17 MeV tritons was used and the reaction protons were momentum analyzed in a quadrupole-three-dipole (Q3D) spectrometer[6] and detected by a helical proportional counter[7] in the focal plane. The proton spectrum obtained at 50° is shown in Fig. 1; typical resolution was 18 keV FWHM. The calibration of radius of curvature and proton energy was done using the well-established level energies of $^{199}$Au.[5] Our experimental results are summarized in Table I, which also presents results from the most recent compilation.[5] Angular distributions were taken in 5° intervals from 15°—60°; differential cross sections as functions of angle are given in Fig. 2. Absolute cross sections were determined by measuring the elastically scattered tritons at 30° using a surface-barrier detector with known solid angle and comparing the results to optical model predictions. Distorted wave Born approximation (DWBA) calculations were performed using the code[8] DWUCK4 and the optical model parameters given in Table II. These parameters are similar to those of (t,p) studies on the Pt nuclei.[1,4]

The characteristic shape of the angular distribution for an $L=0$ transfer enabled more restrictive spin assignments to be made in several cases. The other shapes, $L=2$ and $L=4$, are not as unambiguous, and, given the target spin of $\frac{3}{2}^+$, were not used to make more restrictive $J^\pi$ limitations.

## III. DISCUSSION

As given in Table I and illustrated in Fig. 2, four $L=0$ transitions can be identified in the present (t,p) measurements populating states in $^{199}$Au. However, most of the $L=0$ strength is concentrated in the ground-state to ground-state transition, with the excited state at 791 keV receiving ~4% of the ground state strength. This is in contrast to observations on the $^{195}$Pt(t,p) reaction,[4] where the expected ground-state strength was fragmented into three dominant components. It is not known at this time what mechanism could be responsible for such a dramatic difference in structure between these reactions. The differences between the $^{195}$Pt and $^{197}$Au targets could arise from the blocking effect of the odd neutron in $^{195}$Pt. However, preliminary results[11] from (t,p) reactions on other odd-$Z$ targets in this mass region also show fragmentation of the $L=0$ strength.

In the odd-$A$ Pt nuclei it has now been established[4,12] that many more low-lying $\frac{1}{2}^-$, $\frac{3}{2}^-$ states are observed than can be explained within the framework of the Nilsson model. Our present $^{199}$Au study does not indicate any such anomalous structure. The Nilsson model would allow three low-lying $\frac{3}{2}^+$ states to occur in a moderately deformed nucleus, as are observed in our measurements. The Au nuclei have frequently been investigated as having the characteristics of an asymmetric rotor, either in geometrical models[13] or as examples of the super and spinor symmetries that arise from coupling a $j=\frac{3}{2}$ particle to the $\gamma$-unstable O(6) boson core described within the interacting boson approximation.[14,15] A possible explanation of the dramatic changes in the two-neutron transfer strengths may come from examining the changes in the nonaxial degrees of freedom that could arise from the dependence of the polarizing effect on the core from the single particle orbital occupied by the odd particle.

Another characteristic of the (t,p) reaction in this region is the location and fragmentation of the $L=4$ transfer strength. In Ref. 1 it was observed that the energy centroid of the $L=4$ Pt(t,p) transfer strength changed as a function of neutron number from ~2 MeV in excitation in $^{196}$Pt ($N=118$) to the $4_1^+$ and $4_2^+$ states (at 1.099 and 1.263 MeV) in $^{200}$Pt ($N=122$). The $L=4$ two-neutron transfer strength to states in $^{199}$Au is summarized in Table III. As was also the case for the even Pt(t,p) measurements, the summed $L=4$ transfer strength should only

TABLE III. $L=4$ transfer in the $^{197}$Au(t,p)$^{199}$Au reaction.

| $E_x$[a] (keV) | $\frac{d\sigma}{d\Omega}$ ($\mu$b/sr)[b] | $\frac{\sigma}{\sigma_{g.s.}}$ (%)[c] |
|---|---|---|
| 1396 | 4.5 | 2.9 |
| 1454 | 3.0 | 2.0 |
| 1489 | 5.8 | 3.8 |
| 1568 | 3.0 | 2.0 |
| 1602 | 2.7 | 1.8 |
| 1709 | 16. | 10.4 |
| 1765 | 2.5 | 1.6 |
| $\bar{E}_x=1590(50)$ keV | | $\Sigma\left[\frac{d\sigma}{d\Omega}\right]=38(6)$ $\mu$b/sr |

[a] The excitation energy in keV of $L=4$ transitions (see Table I).
[b] The differential cross section in $\mu$b/sr at 50°.
[c] Cross sections of $L=4$ transitions relative to the ground-state transition.

serve as an indication of the total strength, since $L$ transfer has not been identified for all transitions. However, since all states that are relatively strongly populated [$d\sigma/d\Omega(50°) \geq 4$ $\mu$b/sr] can be assigned $L$ transfers, Table III reflects the dominant $L=4$ strength observed in this reaction.

Comparing the data in this table to the earlier results for $^{196}$Pt(t,p), one finds that the $L=4$ strength for the two isotones occurs with essentially the same centroid ($\sim 1.6$ MeV in excitation), with the strongest components in each case feeding a single state at $\sim 1.7$ MeV in excitation. This similarity in $L=4$ strength gives further support to the argument[16] that the $L=4$ transfer is dominated in this region by $(3p_{1/2}2f_{7/2})$ transfer and that the details of the centroid and strength are governed by the location of the $p_{1/2}$ orbital with respect to the Fermi surface of these nuclei.

## IV. CONCLUSIONS

The $^{197}$Au(t,p)$^{199}$Au reaction has been studied, several previously unobserved levels have been populated, and some firm $J^\pi = \frac{3}{2}^+$ assignments can be made. In contrast to the (t,p) reaction on the $N=117$ nucleus $^{195}$Pt where the $L=0$ transfer strength was highly fragmented, for the $N=118$ nucleus $^{197}$Au, essentially all of the $L=0$ strength is observed to populate the residual $^{199}$Au ground state. The mechanism responsible for this pattern of fragmentation of $L=0$ strength in this mass region is not yet understood. We are in the process of examining two-neutron transfer on other odd-mass targets to further map out the $L=0$ strength and, we hope, to permit an understanding of the mechanism for this effect.

This work was supported by the U. S. Department of Energy.

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[1] J. A. Cizewski, E. R. Flynn, R. E. Brown, D. L. Hanson, S. D. Orbesen, and J. W. Sunier, Phys. Rev. C 23, 1453 (1981).

[2] P. T. Deason, C. H. King, T. L. Khoo, J. A. Nolen, and F. M. Bernthal, Phys. Rev. C 20, 927 (1979).

[3] E. R. Flynn and D. G. Burke, Phys. Rev. C 17, 501 (1978).

[4] J. A. Cizewski, E. R. Flynn, R. E. Brown, and J. W. Sunier, Phys. Rev. C 26, 1960 (1982).

[5] J. Halperin, Nucl. Data Sheets 24, 57 (1978), and references therein.

[6] E. R. Flynn, S. D. Orbesen, J. D. Sherman, J. W. Sunier, and R. Woods, Nucl. Instrum. Methods 128, 35 (1975).

[7] E. R. Flynn, Nucl. Instrum. Methods 162, 305 (1979), and references therein.

[8] P. D. Kunz (unpublished).

[9] E. R. Flynn, D. D. Armstrong, J. G. Berry, and A. G. Blair, Phys. Rev. 182, 1113 (1969).

[10] F. G. Perey, Phys. Rev. 131, 745 (1963).

[11] J. A. Cizewski, E. R. Flynn, R. E. Brown, and J. W. Sunier (unpublished).

[12] D. D. Warner, R. F. Casten, M. L. Stelts, H. G. Börner, and G. Barreau, Phys. Rev. C 26, 1921 (1982); R. F. Casten, D. D. Warner, G. M. Gowdy, N. Rofail, and K. Lieb, *ibid.* 27, 1310 (1983).

[13] C. Vieu, S. E. Larsson, G. Leander, I. Ragnarsson, W. deWieclawik, and J. S. Dionisio, J. Phys. G 4, 531 (1978).

[14] J. Vervier, Phys. Lett. 100B, 383 (1981); J. Vervier, R. Holzmann, R. V. F. Janssens, M. Loiselet, and M. A. van Hove, *ibid.* 105B, 343 (1981).

[15] J. L. Wood, Phys. Rev. C 24, 1788 (1981).

[16] D. Breitig, R. F. Casten, W. R. Kane, G. W. Cole, and J. A. Cizewski, Phys. Rev. C 11, 546 (1975).