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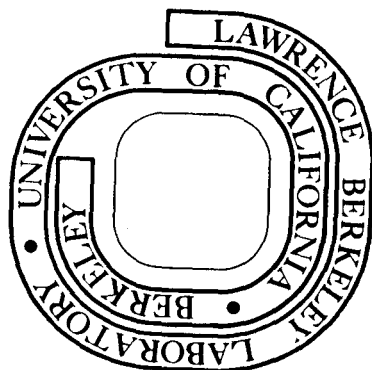
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HIGH-SPIN STATES IN <sup>191, 193, 195</sup>Au

P. O. Tjøm, M. R. Maier, D. Benson, Jr.,  
F. S. Stephens, and R. M. Diamond

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HIGH-SPIN STATES IN  $^{191,193,195}\text{Au}$ <sup>†</sup>

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Abstract

The  $^{191,193,195}\text{Au}$  nuclei have been studied by means of the  $(\alpha, xn\gamma)$  and  $(\text{Li}, xn\gamma)$  reactions. A decoupled band built on the  $h_{11/2}$  orbital has been identified in all three nuclei. Also a considerable number of lower- and intermediate-spin levels based on this orbital have been observed and compared with the expectations from a simple rotation-aligned coupling scheme. Isomeric states were also observed in these three gold nuclei, having an energy of about 2 MeV and probable spin  $21/2^+$ . This state is most likely due to a coupling of the aligned  $h_{11/2}$  hole with the  $5^-$  states observed in the nearby even Pt, Hg, and Pb nuclei. The nature of these  $5^-$  states is discussed.

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Nuclear Reactions  $^{190,192}\text{Os}(\text{Li},\text{xn}\gamma)$ ,  $E_{\text{Li}} = 50, 57, 58 \text{ MeV}$ ;  
 $^{191,193}\text{Ir}(\alpha,\text{xn}\gamma)$   $E_{\alpha} = 26, 29, 42 \text{ MeV}$ ; measured relative gamma  
intensities, coincidences, angular anisotropies; deduced levels, J,  $\pi$ .  
Enriched targets; Ge(Li) detectors.

## 1. Introduction

A number of experimental studies have established the existence of decoupled bands in nuclei; these bands have been rather unambiguously identified in the neutron-deficient La and rare-earth nuclei, in the Hg region, and probably also in the Sc, Se, and Pd regions<sup>1</sup>). In this paper we will report on results from a study of the <sup>191,193,195</sup>Au nuclei.

In the Au nuclei a low-lying  $11/2^-$  state is known<sup>2</sup>), which at first might be thought to be the  $\Omega = 11/2^-$  Nilsson state, indicating a prolate deformation for these nuclei. Recent results show, however, that the nuclei in this mass region are oblate<sup>3-6</sup>), and if this is the case also for the Au nuclei, the  $\Omega = 1/2$  Nilsson orbital is closest to the Fermi surface and, within the context of the strong-coupling model, cannot explain the existence of the known low-lying  $11/2^-$  states. However, the model of a particle coupled to a rapidly-rotating non-spherical core<sup>1,6</sup>) is consistent with the  $11/2^-$  assignment and with the observed band built on this state. The aim of the present study was to test insofar as possible the adequacy of such a rotation-aligned model for the negative-parity levels of this nucleus.

## 2. Experimental Method

Several reactions have been used to populate states in  $^{191,193,195}\text{Au}$ , i.e.,  $\text{Ir}(\alpha, xn\gamma)\text{Au}$  with 26, 29, and 42 MeV  $\alpha$  beams and  $\text{Os}({}^7\text{Li}, xn\gamma)\text{Au}$  with 50 and 58 MeV  ${}^7\text{Li}$  beams. The targets were mounted on thin Al backings and were enriched in  $^{191}\text{Ir}$ ,  $^{193}\text{Ir}$ ,  $^{190}\text{Os}$  and  $^{192}\text{Os}$ . The Berkeley 88" cyclotron provided the alpha and  ${}^7\text{Li}$  beams. The gamma-ray spectra were detected with one or two  $8\text{ cm}^3$  planar and one  $30\text{ cm}^3$  coaxial Ge(Li) detectors. The singles gamma-ray spectra were recorded both in-beam and off-beam, which make it possible to distinguish between prompt transitions and ones which are delayed by  $\gtrsim 3$  nsec. The angular anisotropies were measured with the detectors at  $30^\circ$  and  $90^\circ$  for the  $\alpha$  reactions, and at  $45^\circ$  and  $90^\circ$  for the Li reactions. Gamma-gamma coincidence measurements were performed with both detectors at  $90^\circ$  relative to the beam direction. The 4-dimensional coincidence system used in this work is described in ref. <sup>7</sup>). The relative efficiency of the counters was measured with  $^{177\text{m}}\text{Lu}$  and  $^{152\text{m}}\text{Eu}$  sources.

### 3. Experimental Results

Examples of the singles gamma-ray spectra are illustrated in figs. 1-3. The gamma-ray energies, the relative intensities normalized to 100 for the  $15/2^- \rightarrow 11/2^-$  transitions, the angular anisotropies, and the transition assignments made previously and from this work are listed in Tables 1-3.

A characteristic feature of the spectra, above an energy of 300 keV, is that very few strong transitions are observed. In the energy region around 400 keV all spectra show one strong gamma line, and a relatively strong line is also observed in the 700 keV energy region.

Figure 4 shows typical coincidence spectra, for

$^{191,193,195}\text{Au}$  nuclei, with the gate set on the  $\sim 400$  keV gamma transition.

In these spectra the contribution from the background has been subtracted. The level schemes shown in fig. 5 are all consistent with the measured coincidence spectra.

#### 3.1. THE $^{195}\text{Au}$ NUCLEUS

The  $^{195}\text{Au}$  nucleus has previously been studied<sup>2,8</sup>) from the decay of  $^{195}\text{Hg}$  and of  $^{195\text{m}}\text{Hg}$ . The level scheme proposed by J. Frána et al.<sup>8</sup>) is in good agreement with that given in fig. 5.

As seen from fig. 1 the 388 keV and 718 keV transitions have relatively high intensity. The coincidence measurements show that they are in coincidence with each other and their angular anisotropies are in agreement with stretched E2 assignments. The 388 keV gamma line has also been observed earlier<sup>2,8</sup>) and assigned as the  $15/2^- \rightarrow 11/2^-$  transition. The evidence is therefore strong for



a  $19/2^- - 15/2^-$  assignment for the 718.5 keV transition. These two transitions are the only ones observed in the decoupled band built on the  $11/2^-$  state.

The delayed gamma-gamma coincidence spectra show that the  $19/2^-$  state is fed from an isomeric state, at an excitation energy of 1813 keV, by a 388 keV transition which is not resolved from the  $15/2^- \rightarrow 11/2^-$  one. The lifetime of the isomer is found to be  $8 \pm 2$  ns. The 167 keV transition and part of the 207 keV one (see fig. 4) precede this delay, but are not in coincidence with each other. The level scheme above 1813 keV is not yet very clear.

As pointed out above, the favored band ( $I = j; j + 2, j + 4, \dots$ ) is strongly populated, but transitions in the unfavored band ( $I = j + 1, j + 3, j + 5, \dots$ ) are also observed, where  $j$  is  $11/2$  in this case. The transitions of the type  $I + 1 \rightarrow I$  can be mixed  $M1 + E2$  transitions. In rotational nuclei it is well known that the sign of the mixing ratio,  $\delta = \langle I || E2 || I + 1 \rangle / \langle I || M1 || I + 1 \rangle$ , for such a transition is the same as the sign of  $(g_K - g_R) / Q_0$ , where  $g_K$  is the single-particle gyromagnetic moment. Nakai<sup>5)</sup> has shown that for high-spin states the sign of  $(g_K - g_R)$  is the same as that of  $(g_j - g_R)$  and is known from systematics, so that the sign of  $Q_0$  is determined from the sign of  $\delta$ . For the  $I + 1 \rightarrow I$  transitions the sign of  $\delta$  is usually the same as the sign of  $A_2$ , where  $A_2$  is a coefficient in the general expression for the angular distribution of a gamma ray:

$$W(\theta) = 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta) + \dots \quad (1)$$

The  $7/2^-$ ,  $9/2^-$ , and  $13/2^-$  states have previously been assigned to the energy levels 526, 894, and 879 keV, respectively. The observed transition energies and coincidence data are in agreement with the level scheme given in ref. <sup>8)</sup>, but the  $A_2$  coefficients for the  $I + 1 \rightarrow I$  transitions (369 and 561 keV) are

opposite to the rule given above. The  $A_2$  coefficients, calculated under the assumption that  $A_4 = 0$ , for the 369, 561, and 576 keV transitions are all positive. For the rotation-aligned coupling scheme one can show that the above rule is reversed for the  $I + 1 \rightarrow I$  transitions, so that the sign of  $A_2$  should be opposite to that of  $(g_j - g_R)/Q_0$  for all transitions from the unfavored band to the decoupled band. Thus, for these odd-proton nuclei  $(g_j - g_R)$  is positive and  $Q_0$  in this region is likely to be negative, so that positive  $A_2$  values are expected. Therefore, it happens that the  $A_2$  coefficients have the same sign and are of the same order as for a stretched E2 transition. This makes their unambiguous identification difficult in these gold nuclei, but the results are consistent with the previous spin assignments in all cases.

The 660 keV transition is in coincidence with the  $15/2^- \rightarrow 11/2^-$  transition. The angular anisotropy is similar to the  $9/2^- \rightarrow 7/2^-$  and  $13/2^- \rightarrow 11/2^-$ . Since no decay to any lower spin states could be observed, it is probable that the 660 keV line depopulates a  $17/2^-$  state at an excitation energy of 1366 keV. This is consistent with the absence of population to this state in the decay of  $^{195m}\text{Hg}$  ( $I = 13/2$ ). Also, the fact that we see appreciable population to the 1405 keV state makes its spin most likely to be the highest of the previously possible choices ( $15/2$ ).

The transitions between the positive-parity states up to the 819 keV level have all been observed<sup>8)</sup> in the decay of  $^{195m}\text{Hg}$ . The 557 keV transition was tentatively placed in the previous level scheme, and is confirmed in these measurements. From the coincidence data and the angular anisotropy, the 557 keV gamma line is assigned as the  $9/2^+ \rightarrow 5/2^+$  transition. The 672 keV transition is in coincidence with the 557 keV transition and defines a level at 1490 keV, whose properties are consistent with a spin of  $13/2^+$ .

### 3.2. THE $^{193}\text{Au}$ NUCLEUS

The  $^{193}\text{Hg}$  decay leading to  $^{193}\text{Au}$  has been well studied<sup>2,9</sup>), and an  $11/2^-$  state of 290 keV has been identified. As was the case in  $^{195}\text{Au}$  the strongest transitions observed are associated with the favored band built on the  $11/2^-$  state. In  $^{193}\text{Au}$ , three transitions, 408, 721, and 755 keV were observed in coincidence, instead of only two transitions as with  $^{195}\text{Au}$ . This lack of population in  $^{195}\text{Au}$  may be connected with the lower energy of the isomeric state as discussed later. The angular anisotropies are in agreement with stretched E2 assignments for all three transitions. We consider these to be transitions in the band built on the  $11/2^-$  state with spins  $15/2^-$ ,  $19/2^-$ , and  $23/2^-$  as shown in fig. 5. The energy spacings  $15/2^- \rightarrow 11/2^-$  and  $19/2^- \rightarrow 15/2^-$  are very similar to those observed in  $^{195}\text{Au}$ . There is a 205 keV transition in coincidence with all three of these lines, so that it must precede this cascade. Its intensity in the 58 MeV Li reaction is larger than that of the 755 keV transition, but there is also a contribution to this line from the Coulomb excitation of  $^{192}\text{Os}$ . The 2379 keV level could be the  $27/2^-$  member of the decoupled band, but there is not yet much evidence to support this.

The  $19/2^-$  state in  $^{193}\text{Au}$  at an excitation energy of 1419 keV is also fed by a transition of 529 keV from an isomer at an excitation energy of 1948 keV. The lifetime of the isomer is  $12 \pm 2$  ns. In this case there is also observed a 1250 keV gamma line which follows the isomeric delay and is in coincidence with the 408 keV line. This must be a transition between the isomer and the  $15/2^-$  state. Preceding this isomer are transitions of energy 133 and 194 keV, which

are not in coincidence with each other. This is quite similar to  $^{195}\text{Au}$ , but there is not enough information in either case to construct a reliable level scheme above the isomer.

We can make an estimate of the spin and parity of the 1948 keV isomeric state as follows. The decay to the  $15/2^-$  state rules out spins higher than  $21/2$  due to the nsec lifetime of the isomer. On the other hand, the absence of strong decay to the  $17/2^-$  state at 1374 keV makes a  $19/2$  assignment unlikely. Thus,  $21/2$  seems most consistent for the spin, and positive parity is then indicated, since the lifetime for decay to the  $15/2^-$  state is shorter than expected for a M3 transition. The angular distribution of the 529 keV line is consistent with a stretched dipole with some attenuation due to the 12 nsec lifetime; whereas it would not be for a  $I \rightarrow I$  dipole. This supports the above assignment.

The unfavored levels ( $j + 1, j + 3, \dots$ ) are also observed in  $^{193}\text{Au}$ . The spin assignments for  $13/2^-$  and  $9/2^-$  are in agreement with ref. <sup>9</sup>). The  $17/2^-$  state is placed at an excitation energy of 1374 keV from the coincidence data and arguments similar to those made for  $^{195}\text{Au}$ . The  $A_2$  coefficients calculated from the angular anisotropy, under the assumption that  $A_4 = 0$ , are positive for the mixed M1 + E2 transitions as was the case for  $^{195}\text{Au}$ . The transition energies for the unfavored band are very similar in  $^{193}\text{Au}$  and  $^{195}\text{Au}$ .

Previously there was no positive-parity state known in  $^{193}\text{Au}$  with excitation energy higher than 258 keV ( $5/2^+$ ). From the coincidence measurements and a comparison with  $^{195}\text{Au}$ , the  $7/2^+$ ,  $9/2^+$ , and  $13/2^+$  levels have been placed at excitation energies of 539.3 keV, 809.2 keV, and 1479 keV, respectively. The  $13/2^+ \rightarrow 9/2^+$ ,  $9/2^+ \rightarrow 5/2^+$ , and  $7/2^+ \rightarrow 3/2^+$  transitions all have an angular anisotropy which is in general agreement with a stretched E2 assignment. The  $7/2^+ \rightarrow 5/2^+$  transition has a negative  $A_2$  value which is reasonable for a mixed M1 + E2 transition.

### 3.3. THE $^{191}\text{Au}$ NUCLEUS

No attempt was made to construct a complete level scheme for this nucleus. The transitions of 420 keV, 725 keV, and 775 keV are in coincidence with each other, and the angular anisotropies are in agreement with stretched E2 assignments. Comparison with the  $^{193}\text{Au}$  and  $^{195}\text{Au}$  level schemes strongly suggests that these gamma rays are from the favored band built on the  $11/2^-$  state. The out-of-beam spectra show that the 579.3 keV gamma ray arises from an isomeric state with a half life of  $10 \pm 2$  ns.

The  $^{191}\text{Au}$  nucleus has also been studied from the decay of  $^{191}\text{Hg}$ , ref. <sup>10</sup>). In this work the  $15/2^- \rightarrow 11/2^-$  transition was observed, as well as transitions between the levels with spins  $7/2^-$ ,  $9/2^-$ , and  $13/2^-$ . These transitions are also observed in our singles spectra but we have not made the relevant coincidence measurements. From the analogy with  $^{195,193}\text{Au}$ , these assignments are probably correct. In the decay work <sup>10</sup>) a level at 540 keV is also observed which has tentatively been assigned as  $11/2^-$  or  $13/2^-$ . In  $^{193}\text{Au}$  and  $^{195}\text{Au}$  no analogous energy level has been observed in the present, nor in any previous, work. We do not observe this state in  $^{191}\text{Au}$ , but a weak population cannot be excluded. Since such a level is not expected at this energy on the basis of the rotation-aligned scheme, it would be important to establish its existence or non-existence.

#### 4. Discussion

In the  $^{191,193,195}\text{Au}$  nuclei the favored bands are well established.

Figure 6 shows the bands in comparison with the corresponding bands in doubly-even Pt and Hg nuclei. As seen from the figure, the  $11/2^- \rightarrow 15/2^-$  energy spacings are very close to the  $0^+ \rightarrow 2^+$  energy spacing in the Hg isotopes, whereas the  $0^+ \rightarrow 2^+$  energy spacing in the Pt isotopes are somewhat smaller. For the higher spins, the agreement between the energy spacings is also much better for Au and Hg than for Au and Pt. In the Pt isotopes, the number of empty levels available to the proton pairs is two rather than one, as it is for Hg and Au. This might be the reason for the greater similarity of the energy spacings in Au and Hg.

Apart from the decoupled band levels having spins  $7/2^-$ ,  $9/2^-$ ,  $13/2^-$ , and  $17/2^-$ , are observed at excitation energies which do not differ more than 20 keV for  $^{193}\text{Au}$  and  $^{195}\text{Au}$ . From the study of the decay of  $^{191}\text{Hg}$ ,  $7/2^-$ ,  $9/2^-$ , and  $13/2^-$  levels are also observed in  $^{191}\text{Au}$  at about the same excitation energy as in the other Au nuclei. Since these three Au nuclei are so similar, a comparison between the observed and calculated energy levels is only made for one case and this is shown for  $^{195}\text{Au}$  in fig. 7.

The calculation, similar to those previously made, is based on a particle-plus-rotor model, using a perfect (rigid) rotor Hamiltonian for the core. Thus, it does not include the possibility of asymmetric shapes, shape changes, vibrations, or large individual 2-qp components. All of these effects might be expected to occur in the Au region, so that the calculations in fig. 7 should only be considered as a first approximation. The calculation has no parameters. The  $\hbar^2/2\mathcal{I}$  and  $\beta$  values were derived from the average  $2^+$  energy in  $^{194}\text{Pt}$  and  $^{196}\text{Hg}$  according to expressions given in ref. <sup>1</sup>). This is about the same result one would get by basing these quantities on an average  $\hbar^2/2\mathcal{I}$  value from the  $2^+$  and  $4^+$  states in  $^{196}\text{Hg}$ .

Even with this relatively crude calculation the agreement between the experimental results and the calculation is rather convincing. The decoupled-band members ( $11/2$ ,  $15/2$ , and  $19/2$ ) reflect the core energies, and would be improved by using core spacings more realistic than those of the rigid rotor, as can be seen in fig. 6. The  $7/2$  and  $3/2$  states are approximate members of this band, but since  $I < j$  in these cases, they are more accurately given as  $\kappa = 7/2$  and  $3/2$  states (ref. <sup>1</sup>), where  $\kappa$  is the projection of  $I$  on  $j$ . This is the first time such low-spin states have been seen associated with a decoupled band, and their qualitative agreement with the calculation suggests that the rotation-aligned coupling scheme may apply to low-spin, as well as high-spin, states. The  $13/2$  and  $17/2$  states are members of the  $\alpha = j - 1 = 9/2$  band (sometimes called the unfavored band), and the fact that this band lies considerably lower than calculated can be caused by non-axial shapes. Such shapes are likely to be important in the gold region as indicated by the low-lying second  $2^+$  states in the even-even Pt and Hg nuclei. The  $9/2$  state is an approximate member of this band, but is more accurately represented by a  $\kappa = 7/2$  wave function. The second  $11/2$  and  $15/2$  states would belong to the  $\alpha = 7/2$  band, and the second  $13/2$  state to the  $\alpha = 5/2$  band. Figure 7 shows all the experimental negative-parity states below 1.25 MeV, and all the calculated ones below 2.3 MeV. The significant features of the comparison seem to us to be a) the agreement in energy of the decoupled band and of the 6 or 8 lowest-energy states, and b) the occurrence, in general, of the correct states in the energy region shown. Calculations including shape asymmetry have been made<sup>11</sup>), and seem to provide a major improvement over the comparison in fig. 7.

These gold nuclei illustrate rather clearly that a weak-coupling scheme is not appropriate. All members that would come from the multiplet based on the

lowest  $2^+$  core state are seen in  $^{195}\text{Au}$  ( $7/2^-$ , 526;  $15/2^-$ , 706;  $13/2^-$ , 879;  $9/2^-$ , 894; and  $11/2^-$ , 1280), and their splitting is considerably larger than the core  $2^+$  to  $0^+$  separation, and comparable with the  $4^+$  to  $2^+$  spacing. Thus, even though the decoupled band closely approximates the Hg core energies, a weak-coupling explanation of these levels could not be very accurate.

In the odd Hg nuclei a negative-parity band with spins  $21/2^-$ ,  $25/2^-$ , and  $29/2^-$  has been observed<sup>12</sup>). The interpretation which has been given is that these states are based mainly on an  $i_{13/2}$  neutron coupled to the negative-parity  $5^-$ ,  $7^-$ , and  $9^-$  states, which occur systematically in the doubly-even Pt, Hg, and Pb nuclei in this region. If the  $5^-$ -state configuration is primarily such a two-neutron state involving an  $i_{13/2}$  neutron with maximum alignment along the direction of  $I$  ( $\alpha = 13/2$ ), the Pauli exclusion principle would require that the addition of another  $i_{13/2}$  neutron in the odd-mass case could have a maximum projection along  $I$  of only  $11/2$  ( $\alpha = 11/2$ ), so that the total spin in the Hg nuclei would indeed be  $21/2$ ,  $[(\nu i_{13/2}, \nu p_{3/2})_5^-, \nu i_{13/2}]_{21/2}^-$ , rather than  $23/2$ , in agreement with experiment. With the Au isotopes, the isomeric levels observed have tentatively been given the assignment  $21/2^+$  which could be based on the  $h_{11/2}$  proton coupled to the  $5^-$  state. Again the configuration of the  $5^-$  state is probably mainly the two-neutron one  $[i_{13/2}, p_{3/2}]_5^-$ , rather than the two-proton one  $[h_{11/2}, s_{1/2}]_5^-$  which is also possible, because in this case the maximum possible spin of  $21/2$  is obtained. That is, the configuration  $[(\nu i_{13/2}, \nu p_{3/2})_5^-, \pi h_{11/2}]_{21/2}^+$  gives spin  $21/2$  rather than the value  $19/2$  which would be expected for the three-proton configuration  $[(\pi h_{11/2}, \pi s_{1/2})_5^-, \pi h_{11/2}]_{19/2}^+$ . It could be that the composition of the  $5^-$  state changes with neutron or proton number in this region, and the odd-A bands based on it provide an excellent means to detect such a change.



The nature of the band built on the  $5^-$  level in the doubly-even nuclei is interesting. The energy spacings, both the small separations and the irregularities, suggest considerable two-particle character; whereas the  $B(E2)$  values ( $\sim 30$  spu, like the ground-state band) show some collective character. Collective  $5^-$  states might be expected in this almost-full shell region from the configurations  $[\nu i_{13/2}, \nu p_{3/2}]$  and  $[\pi h_{11/2}, \pi s_{1/2}]$  much like the collective octupole,  $3^-$ , states could be expected in the nearly-empty shell region from  $[\nu i_{13/2}, \nu f_{7/2}]$  and  $[\pi h_{11/2}, \pi d_{5/2}]$ . This should be a general feature of these shells. If one further considers that the nucleon-nucleon force is attractive in the singlet-even state for like particles, then one should expect that the lowest-lying states from the various two-particle configurations should have the particles in the singlet state, and should also have maximum overlap of the spatial wave functions. This results in the states of natural parity lying lowest. In the present case, this means the states of odd spin. One then expects the following lowest-lying states, in order of increasing energy for each multiplet; for neutrons;  $5^-$ ,  $7^-$  from  $[i_{13/2}, p_{3/2}]$ ,  $7^-$  from  $[i_{13/2}, p_{1/2}]$ ,  $9^-$ ,  $7^-$ , and  $5^-$  from  $[i_{13/2}, f_{5/2}]$ ; for protons;  $5^-$  from  $[h_{11/2}, s_{1/2}]$ ,  $7^-$ ,  $5^-$  from  $[h_{11/2}, d_{3/2}]$ . If one considers mixing these states, and also allowing the core states to couple with them and admix, then the observed levels seem plausible. However, a convincing calculation has not yet been made.

In this connection the 1250 keV E3 transition in  $^{193}\text{Au}$  is interesting. No analogous transition is seen from any  $5^-$  state in this region nor from the  $[5^-, i_{13/2}]_{21/2^-}$  states in the odd-A Hg nuclei. Nevertheless, the experimental evidence placing the 1250 keV line between the 1948 keV isomeric state and the 698 keV  $15/2^-$  state is excellent, and the spin and interpretation of the 1948 keV

isomer seem rather convincing to us. Two facts may be relevant to the solution of this puzzle. First the  $B(E1)$  values are considerably smaller in these gold nuclei than in the even or odd Hg nuclei, and are somewhat smaller for  $^{193}\text{Au}$  than for  $^{191}\text{Au}$  and  $^{195}\text{Au}$ . This would favor E3 competition in this particular case. Also in the Au nuclei, the stretched nature of the isomer,  $5^- + 11/2^- \rightarrow 21/2^+$ , will presumably restrict considerably the proton contribution to the  $5^-$  component, since the aligned  $11/2$  configuration is blocked by the odd particle. This might have a greater effect on the various transition probabilities than on the energies. The 1250 keV E3 transition is enhanced  $\sim 5$  times over the Weiskopf estimate, a value which seems somewhat plausible in terms of the proposed structure of this state.

Two other comments should probably be made about these  $21/2^+$  isomers. First, there are low-energy transitions ( $\sim 150$  keV) preceding the isomers, so that bands of the type seen in the even and odd Hg isotopes probably exist. Our data, however, do not allow us to propose a sufficiently reliable structure. Second, the absence of any evidence for the  $23/2^-$  decoupled-band member in  $^{195}\text{Au}$  is very likely connected with preferential decay from high-spin states into the  $21/2^+$  band rather than into the decoupled band. The  $\sim 150$  keV lower energy of the  $21/2^+$  level in  $^{195}\text{Au}$  relative to  $^{191,193}\text{Au}$  could easily be enough to cause this shift in population.

Finally, it should be pointed out that there also appear to be some simple structural effects in the low-lying even-parity states in  $^{193}\text{Au}$  and  $^{195}\text{Au}$ . However, the interpretation of these states probably requires consideration of more than one j-shell ( $s_{1/2}$  and  $d_{3/2}$ ), so that we have not undertaken it here.

### 5. Conclusions

The odd-mass gold nuclei provide an excellent example of the states resulting from coupling an  $h_{11/2}$  proton hole to the (oblate) even core states. The decoupled band is observed up to spin  $23/2$ , and in addition a variety of other states between  $I = 3/2$  and  $17/2$  are known. The results are in qualitative agreement with the expectations based on a simple, axially-symmetric particle-plus-rotor model. The inclusion of axial-asymmetry can considerably improve this agreement, but the present calculations have not included this feature. These gold nuclei probably offer the most detailed comparison yet available between experiment and calculations of this type.

Two other kinds of levels are seen in these gold nuclei. Isomeric states with probable spins of  $21/2^+$  are seen in all three nuclei, and probably result from the  $h_{11/2}$  proton hole coupled with the well-known core  $5^-$  states. While a plausible structure exists for these  $5^-$  states, a number of unexplained features remain. In addition, there are systematically occurring bands based on the low-lying positive-parity levels in these gold nuclei. These states are very likely based on the  $s_{1/2}$  and  $d_{3/2}$  orbitals, but the appropriate two-shell calculations are not available for comparison.

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References

- 1) F. S. Stephens, R. M. Diamond, J. R. Leigh, T. Kammuri, and K. Nakai, Phys. Rev. Letters 29 (1972) 438; see references in, F. S. Stephens, Proceedings of the International Conference on Nuclear Physics, Munich, 1973, ed. J. de Boer and H. J. Mang, Vol. II, p. 367.
- 2) Nuclear Data Sheets 8 No. 5 (1972).
- 3) J. E. Glenn, R. J. Pryor, and J. X. Saladin, Phys. Rev. 188 (1969) 1905.
- 4) J. O. Newton, S. D. Cirilov, F. S. Stephens, and R. M. Diamond, Nucl. Phys. A148 (1970) 593.
- 5) K. Nakai, Phys. Letters 34B (1971) 269.
- 6) F. S. Stephens, R. M. Diamond, D. Benson, Jr., and M. R. Maier, Phys. Rev. C7 (1973) 2163.
- 7) J. Gizon, A. Gizon, M. R. Maier, R. M. Diamond, and F. S. Stephens, submitted to Nucl. Phys.
- 8) J. Frána, A. Špalek, M. Fišer, and A. Kokeš, Nucl. Phys. A165 (1971) 625.
- 9) Z. Plajner, J. Frána, I. Řezanka, A. Špalek, and M. Fišer, Z. Physik 233 (1970) 122.
- 10) H. Beuscher, P. Jahn, R. M. Lieder, and C. Mayer-Böricke, Z. Physik 247 (1971) 383.
- 11) J. Meyer ter Vehn, private communication (1974).
- 12) D. Proetel, D. Benson, Jr., A. Gizon, J. Gizon, M. R. Maier, R. M. Diamond, and F. S. Stephens, submitted to Nucl. Phys.

Table 1. Transitions in  $^{195}\text{Au}$ .

Energy keV	$^{193}\text{Ir} + 26 \text{ MeV } \alpha$		Assignment	
	90°	30°/90°	Previous	Present
167.0 <sup>a</sup>	6.2	2.15		
180.2	5.7	0.87	$3/2^+ \rightarrow 1/2^+$	
200.4	6.8	2.33	$5/2^+ \rightarrow 1/2^+$	
207.2 <sup>a,b</sup>	21.1	1.00	$7/2^- \rightarrow 11/2^-$	
261.9	178.9	0.87	$5/2^+ \rightarrow 3/2^+$	
288.0	4.5	0.95	$5/2^+, 7/2^+ \rightarrow 5/2^+$	$7/2^+ \rightarrow 5/2^+$
368.6	5.9	1.06	$9/2^- \rightarrow 7/2^-$	
388.1 <sup>b</sup>	100.0	1.15	$11/2^- \rightarrow 15/2^- \rightarrow 11/2^-$	$15/2^- \rightarrow 11/2^-, 21/2^+ \rightarrow 15/2^-$
439.8	13.2	0.73		
442.1	9.3	0.45		
526.3	17.8	0.97	$11/2^-, 13/2^-, 15/2^- \rightarrow 13/2^-$	$(15/2^- \rightarrow 13/2^-)$
549.8	17.1	1.26	$5/2^+, 7/2^+ \rightarrow 3/2^+$	$7/2^+ \rightarrow 3/2^+$
556.8	15.8	1.31		$9/2^+ \rightarrow 5/2^+$
560.7	21.8	1.08		$13/2^- \rightarrow 11/2^-$
576.1	3.1	1.35	$9/2^- \rightarrow 11/2^-$	
659.5	14.2	0.95		$(17/2^- \rightarrow 15/2^-)$
671.7	6	~ 1		$(13/2^+ \rightarrow 9/2^+)$
718.5	36.1	1.28		$19/2^- \rightarrow 15/2^-$

<sup>a</sup>Precedes  $21/2^+$  isomer.<sup>b</sup>Double.

Table 2. Transitions in  $^{193}\text{Au}$ .

Energy keV	$^{192}\text{Os} + 58 \text{ MeV } ^7\text{Li}$		$^{191}\text{Ir} + 26 \text{ MeV } \alpha$		Assignment	
	90°	45°/90°	90°	30°/90°	Previous	Present
133.1 <sup>a</sup>	14.1	1.37				
186.6			10.9	0.74	( $3/2^+$ , $1/2^+ \rightarrow 1/2^+$ )	
193.5 <sup>a</sup>	30.1	1.08				
205.2 <sup>b</sup>	72.8	1.11				
218.1			30.7	1.03	$7/2^- \rightarrow 11/2^-$	
219.9			11.6	1.03	$5/2^+ \rightarrow 1/2^+$	
258.1	38.1	0.97	288.7	0.87	$5/2^+ \rightarrow 3/2^+$	
281.5	6.4	1.06	10.4	0.77		$7/2^+ \rightarrow 5/2^+$
382.2			44.9	1.66	$9/2^- \rightarrow 7/2^-$	
407.8	100.0	1.16	100.0	1.41	$15/2^- \rightarrow 11/2^-$	
528.7	33.9	0.80	22.9	0.94		( $21/2^+ \rightarrow 19/2^-$ )
535.7			14.3	1.19		( $15/2^- \rightarrow 13/2^-$ )
539.3			20.1	1.24		$7/2^+ \rightarrow 3/2^+$
551.2			17.2	1.19		$9/2^+ \rightarrow 5/2^+$
573.6			34.2	1.43	( $11/2^-, 13/2^- \rightarrow 11/2^-$ )	$13/2^- \rightarrow 11/2^-$
600.9	10.4	1.04	~ 8	~ 1.7	$9/2^- \rightarrow 11/2^-$	
669.8	10.7	1.77	13.5	1.23		$13/2^+ \rightarrow 9/2^+$
675.7			6.8	1.49		( $17/2^- \rightarrow 15/2^-$ )
721.2	77.8	1.20	41.3	1.17		$19/2^- \rightarrow 15/2^-$
754.5	32.5	1.27				$23/2^- \rightarrow 19/2^-$
1250.1	~ 10					( $21/2^+ \rightarrow 15/2^-$ )

<sup>a</sup>Precedes  $21/2^+$  isomer.

<sup>b</sup>Includes a contribution from  $^{192}\text{Os}$  Coulomb excitation.

Table 3. Transitions in  $^{191}\text{Au}$ .

Energy keV	$^{190}\text{Os} + ^7\text{Li}$ + 57 MeV		Assignment	
	90°	45/90°	Previous	Present
419.9	100.0	1.15	$15/2^- \rightarrow 11/2^-$	
579.3	59.6	0.96	$(21/2^+ \rightarrow 19/2^-)$	
725.5	56.4	1.48	$19/2^- \rightarrow 15/2^-$	
775.2	20.0	1.26	$23/2^- \rightarrow 19/2^-$	

Figure Captions

- Fig. 1. In-beam gamma-ray spectra of the  $^{193}\text{Ir}(\alpha,2n\gamma)^{195}\text{Au}$  reaction taken with an  $8\text{ cm}^3$  planar Ge(Li) detector placed at  $30^\circ$  and  $90^\circ$  to the beam axis.
- Fig. 2. In- and off-beam gamma-ray spectra of the  $^{191}\text{Ir}(\alpha,2n\gamma)^{193}\text{Au}$  reaction taken with an  $8\text{ cm}^3$  planar Ge(Li) detector placed at  $90^\circ$  to the beam axis.
- Fig. 3. In-beam gamma-ray spectrum of the  $^{190}\text{Os}(^7\text{Li},6n\gamma)^{191}\text{Au}$  reaction taken with an  $8\text{ cm}^3$  planar Ge(Li) detector placed at  $45^\circ$  to the beam axis.
- Fig. 4. Gamma-ray coincidence spectra for  $^{191,193,195}\text{Au}$  with the gates set at 408, 388, and 420 keV.
- Fig. 5. The decay schemes for  $^{191}\text{Au}$ ,  $^{193}\text{Au}$ , and  $^{195}\text{Au}$ . The widths of the arrows indicate the relative intensities of the transitions following the  $(\alpha,2n\gamma)$  reaction for  $^{193}\text{Au}$  and  $^{195}\text{Au}$  and the  $(\text{Li},6n)$  reaction for  $^{191}\text{Au}$ .
- Fig. 6. The bands based on the  $11/2^-$  state in the odd-mass Au nuclei compared to the ground-state bands in the adjacent Hg and Pt nuclei.
- Fig. 7. A comparison of the observed negative-parity levels in  $^{195}\text{Au}$  with those calculated from a particle-plus-symmetric-rotor model. The heavy, dashed lines indicate levels not observed in this work, but taken from ref. <sup>8</sup>).



Fig. 1

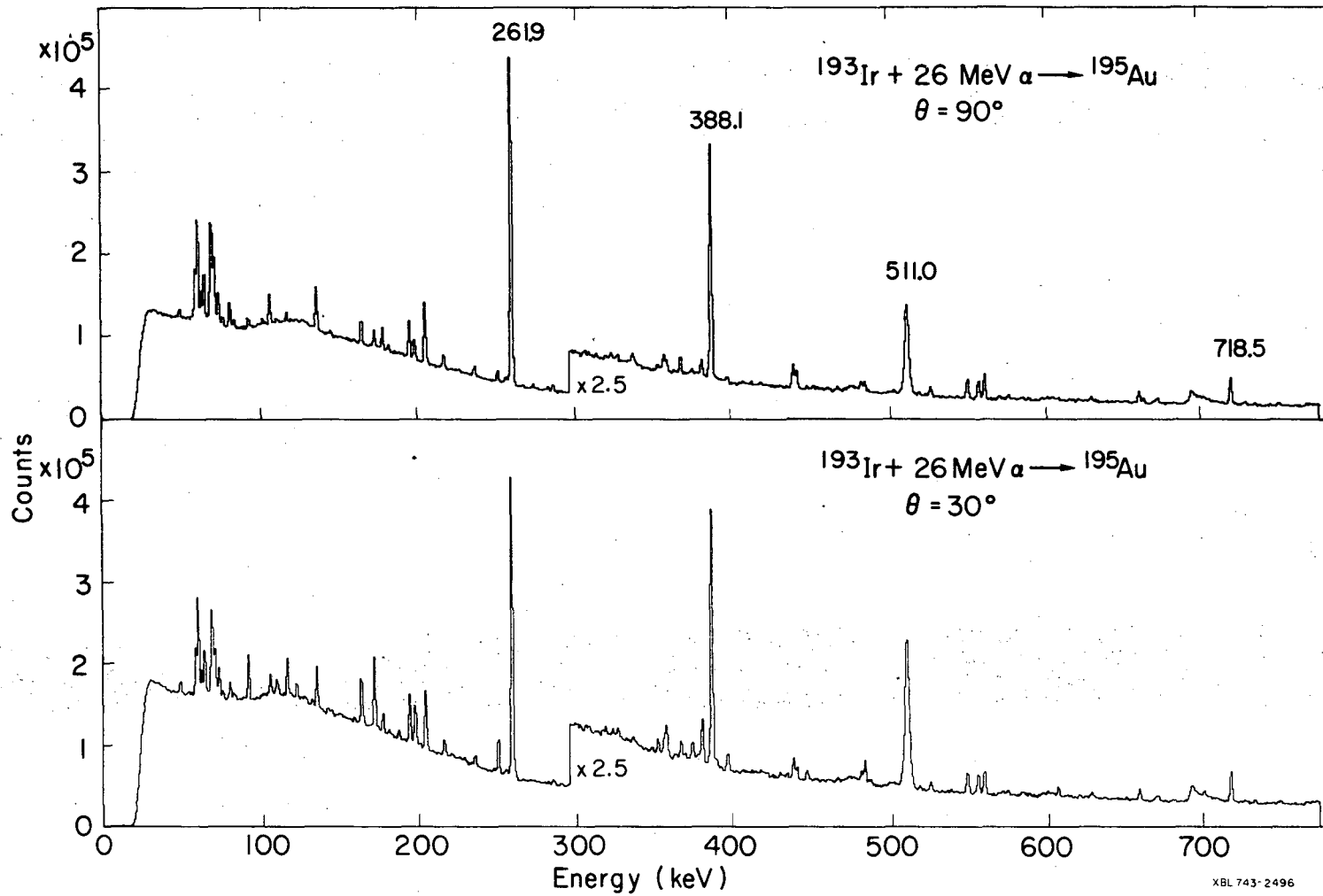
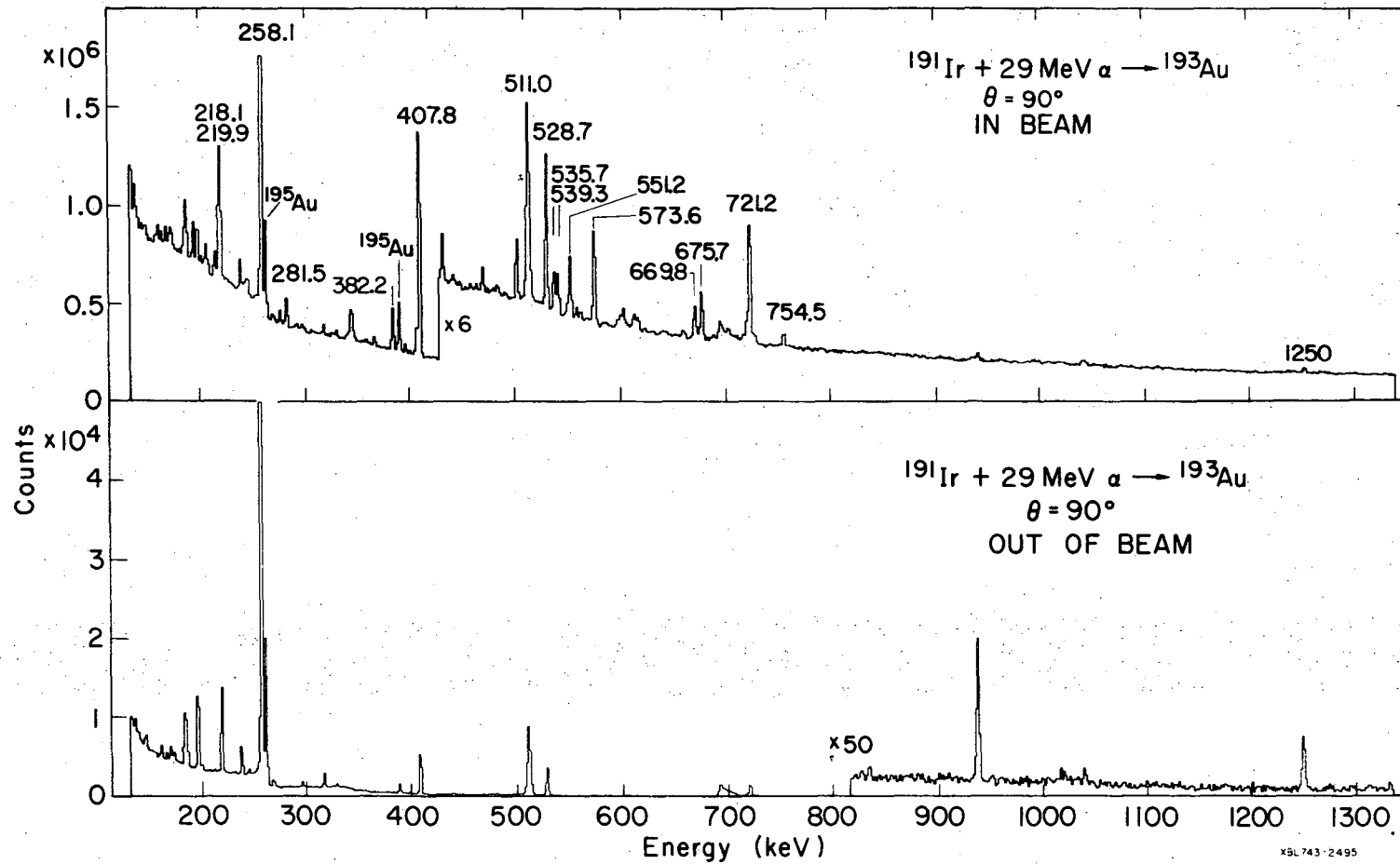


Fig. 2



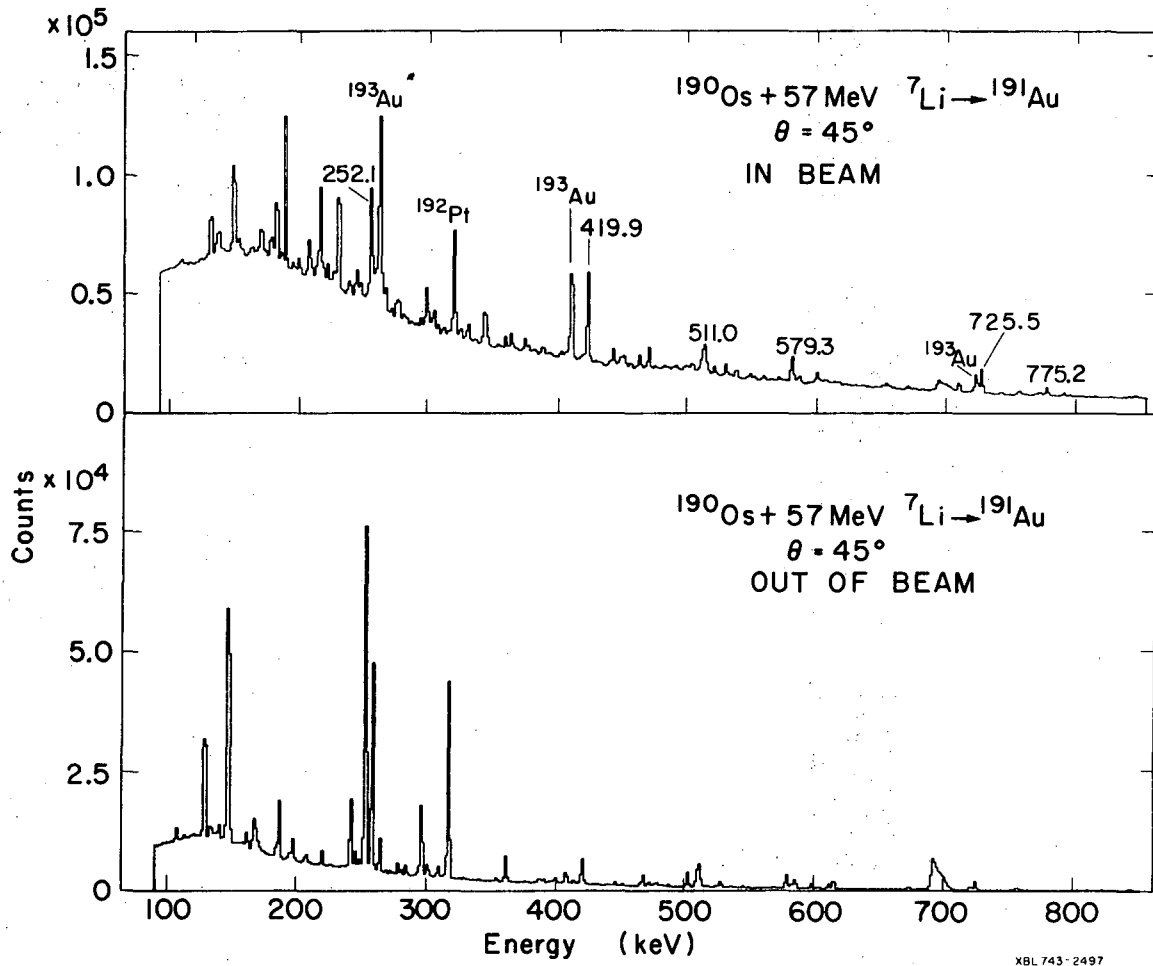


Fig. 3

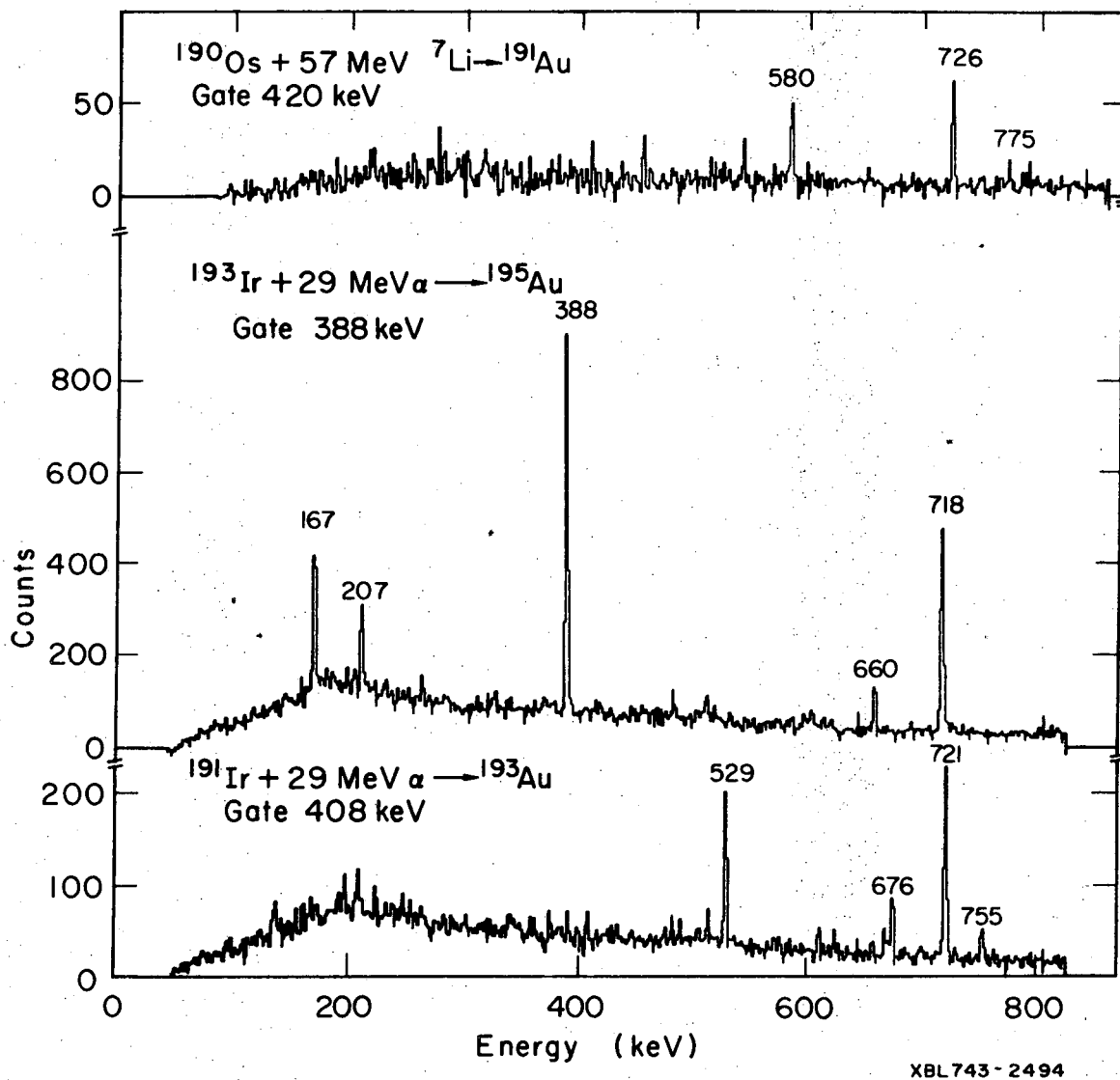
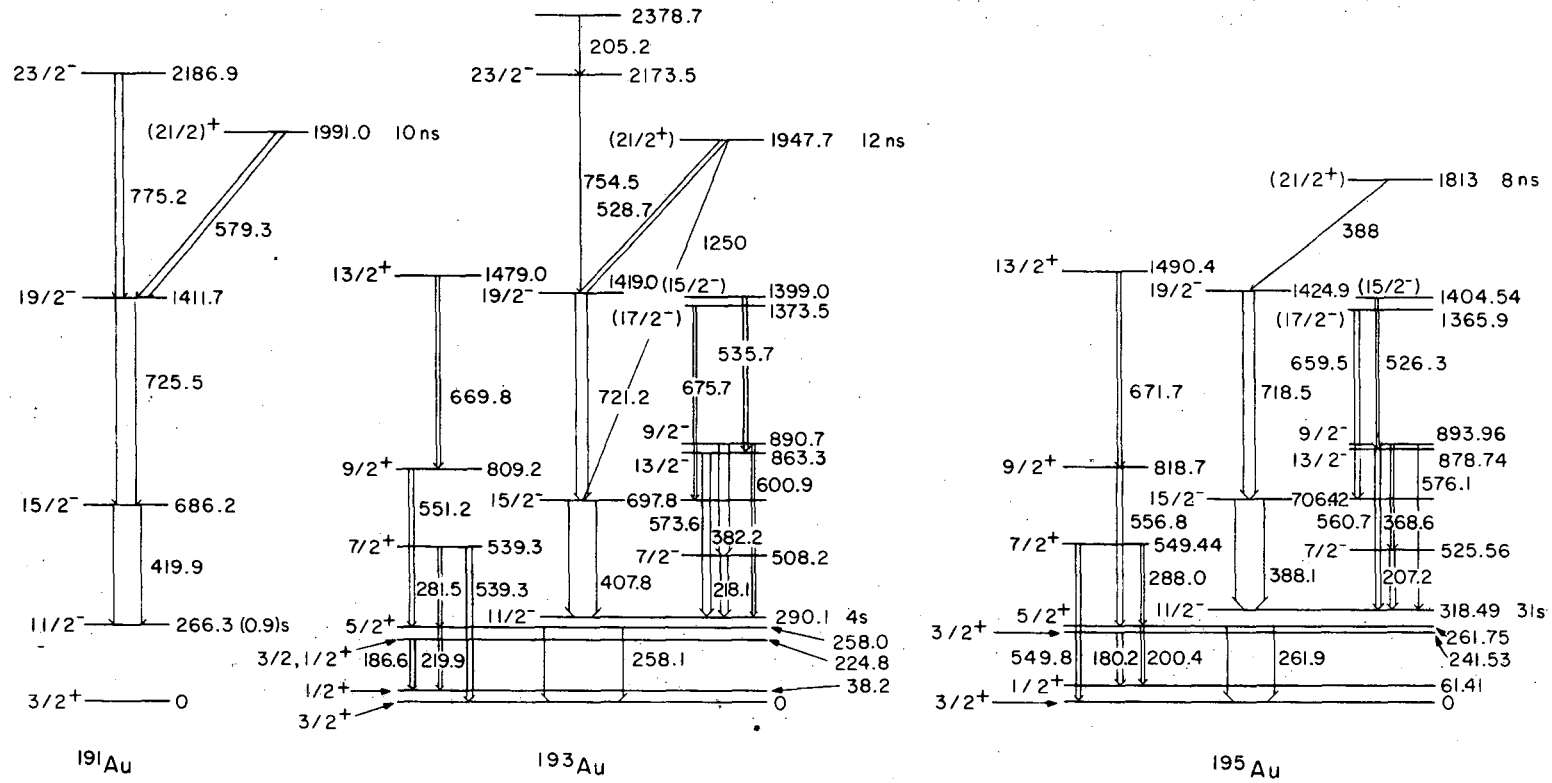


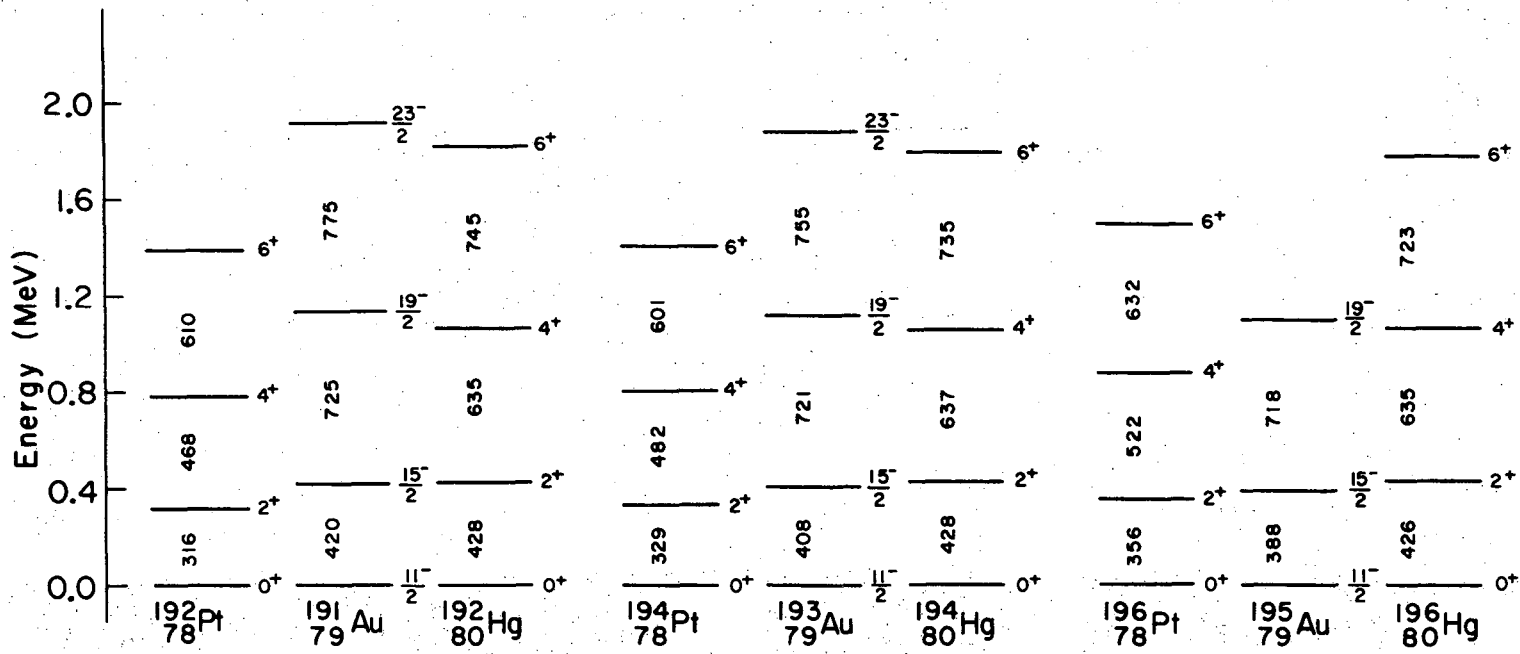
Fig. 4

Fig. 5

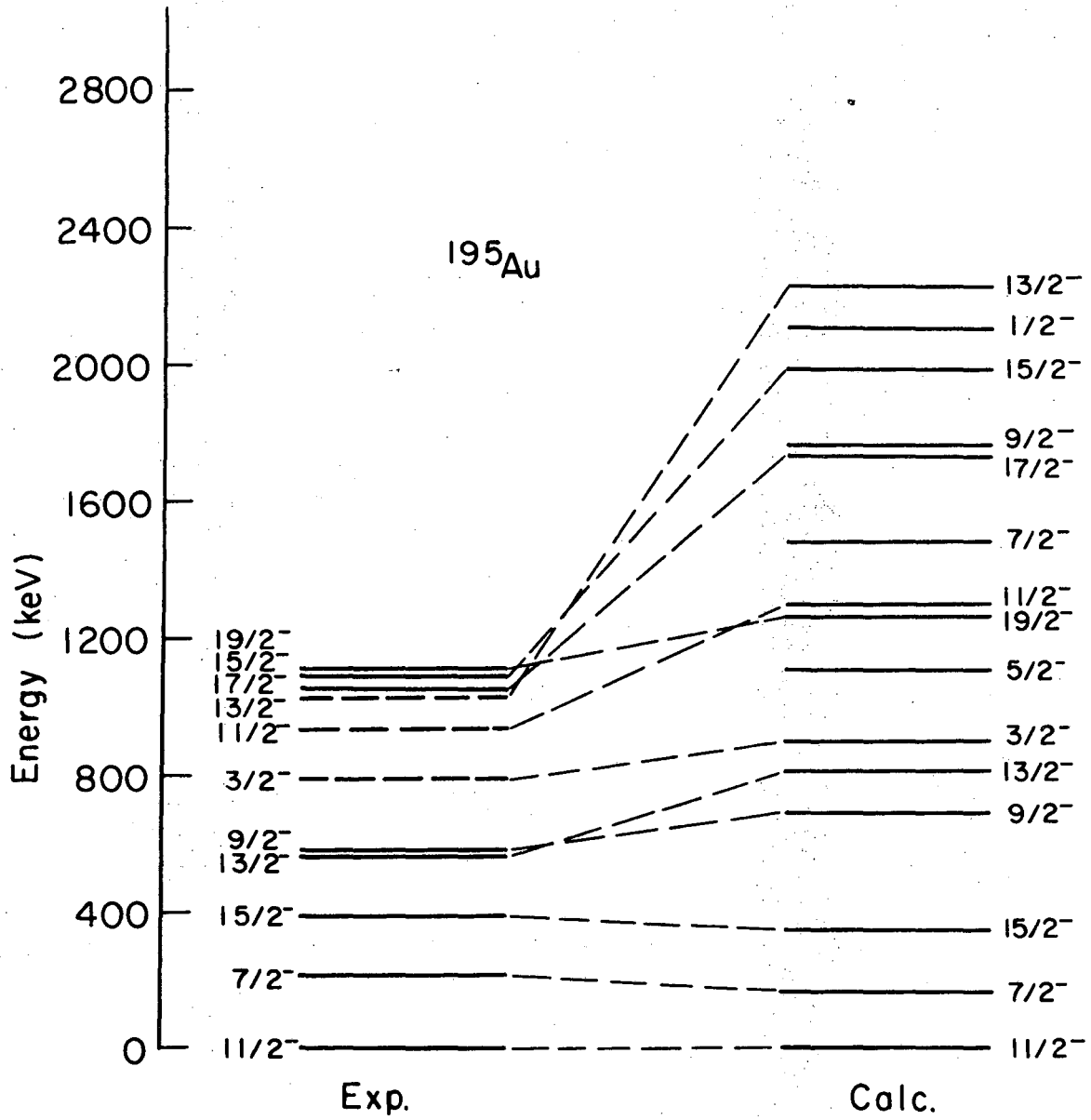


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Fig. 6



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XBL743-2492

Fig. 7

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