79

THE STRUCTURE OF THE 77 KEV STATE OF Au-197

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ABSTRACT. The half-life of the 77 keV state in Au-197 is measured with a Green and Bell type of time-to-amplitude convertor and a 100-channel analysor. An electron-electron coincidence method is employed and the slope method is adopted. The value of the half-life of the 77 keV state is obtained as (1·95±0·06) *ns*. The $M1$ and $E2$ gamma-ray transition probabilities of the 77 keV transition are estimated from the measured half-life and are compared with the single particle estimates. An $M1$ hindrance of (363±22) and an $E2$ enhancement of (17·5±3·5) are observed in the present case. The models proposed by DeShalit and Kisslinger and Sorensen are tested for their applicability. Assuming the ground state wave-function of Kisslinger and Sorensen and with an empirical choice of the amplitude parameters for the 77 keV state, the estimated values are compared with the experimental data. It is observed that the wavefunction of the 77 keV state should contain sizable contributions of the particle and 3/2+phonon amplitudes.

INTRODUCTION

The properties of the low energy states in Au-197 are studied from electron capture decay of Hg-197 and Hg-197m, beta decay of Pt-197 and Pt-197m and Coulomb excitation. The recent studies, carried out in detail, are those of Helmer and McIsaac (1965) and Haverfield *et al.* (1965). The main features of the decay scheme are shown in figure 1. The ground state of Pt-197 as well as that of

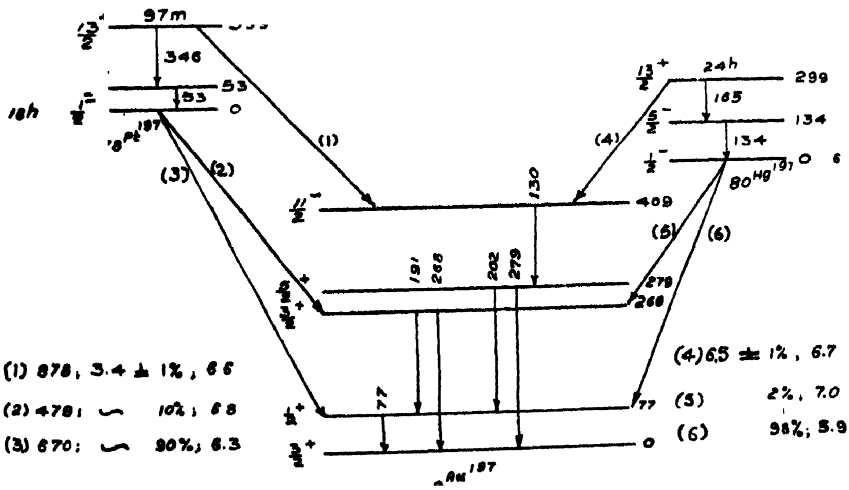

Figure 1. The main features of the level scheme of Au^{197}.

Hg-197 is $1/2^-$ and correspond to the $p_{1/2}$ configuration for the 119th and 117th neutrons respectively according to the shell model assignment. Likewise, the isomeric states Pt-197m and Hg-197m are of $i_{13/2}$ configurations. The ground state of Au-197 is established to be $3/2^+$ and is assigned a $d_{3/2}$ orbital for the 79th proton. The character of the 77 keV state is fixed as $1/2^+$. The lifetime of this level was determined earlier; but the errors involved in the measurements were quite large. Sunyar (1953) obtained a value of $(1{\cdot}9 \mp 0{\cdot}2)$ *ns* for the half-life of this state employing a delayed coincidence method. Subsequent investigations of Nagle *et al.* (1960) and Roberts and Thompson (1963) using Mossbauer techniques yielded values for the half-life as 0·57 *ns* and $(1{\cdot}93 \mp 0{\cdot}2)$ *ns* respectively. It is therefore felt desirable to remeasure the half-life of this state using a time-to-height converter with improved accuracy.

The wavefunctions of the 77 keV state in Au-197 from the De Shalit's core-excitation model (Braunstein and De-Shalit (1962), De-Shalit (1965), McKinley and Rinard (1966) and from the model of Kisslinger and Sorensen (1963) are widely divergent. While the former assumes this state to be arising purely from coupling the $d_{3/2}$ particle with the 2^+ state of the core, the latter assumes it to be essentially arising from quasi-particle excitation. Thus while De-Shalit's model does not allow any particle contribution to the 77 keV state, the model of Kisslinger and Sorensen proposes a 92% contribution of the $s_{1/2}$ of this state. It is therefore of interest to analyse the transition probabilities derived from the lifetime measurement to throw light on the structure of the 77 keV state.

EXPERIMENTAL DETAILS

Apparatus : The experimental arrangement described in an earlier paper (Rama Rao *et al.*, 1967) is adopted in the present investigation. It is a conventional slow-fast coincidence assembly which includes a time-to-amplitude converter of the type developed by Green and Bell (1958). Plastic scintillators (type NE102 with conical wells and of effective thickness 1 mm each) mounted on RCA-6810A photo-multipliers are used as detectors. Conversion electrons feeding and depopulating the state are used as the early and late radiations. The fast channel pulses, derived from the anodes of the photomultipliers, are shaped, using E88CC limiters and RG-63/U clippers. The time-to-amplitude converter is assembled with 6BN6, and is arranged for an input sensitivity of 1 volt. The time spectrum is recorded on a 100-channel analyser, gated by the slow-channel pulses. These slow-channel pulses are derived from the height dynodes of the photomultipliers, and are passed through amplifiers and pulse height analysers to effect the energy analysis. The coincidence output of the two energy channel pulses opens the gate of the 100-channel analyser. The experimental set-up is first employed to study its prompt behaviour, by recording the beta-gamma coincidences using a Co^{60} source. The resultant prompt curve yielded a full-width at half-maximum of $7{\cdot}6\times10^{-10}$ sec. and an intrinsic slope of $8{\cdot}02\times10^{-11}$ sec.

The source Hg^{197} (together with its isomer) is produced at the Bhabha Atomic Research Centre, Bombay, India by the pile neutron irradiation of G.R. grade mercuric oxide, and is supplied in liquid form as mercuric nitrate in nitric acid, with a specific activity of 50 mc/gm. The experimental source is prepared by evaporating a few drops of the source liquid on a thin Mylar foil. A small amount of Hg^{197m} produced along with Hg^{197} decayed considerably at the time of recording the spectra. Hg^{203} activity is present as an impurity in the source. However, it does not affect the present measurements in view of the energy channel settings.

Measurements : The half-life of the 77 keV state is determined by observing the coincidence count distribution between the *K*-conversion electrons of the 191 keV transition feeding this state and the *L*-conversion electrons of the 77 keV transition depopulating the state. The former group is selected differentially (20% window) at 110 keV in the early channel while the latter group is selected differentially (20% window) at 55 keV in the late channel. Both the photomultipliers are operated at 2100V and are arranged in 180° position. The time spectrum is recorded on the 100-channel analyser, the chance rate is deducted and the resulting spectrum is obtained. The spectrum thus obtained in one of the trials is shown in figure 2. Preliminary investigations on the time spectrum obtained with a prompt source, under identical experimental conditons, indicated that the slope method could be adopted for the present case. In the above experiment, the delays are so adjusted that the slope on the right side represents the half-life of the 77 keV state. The observed points on this side are therefore

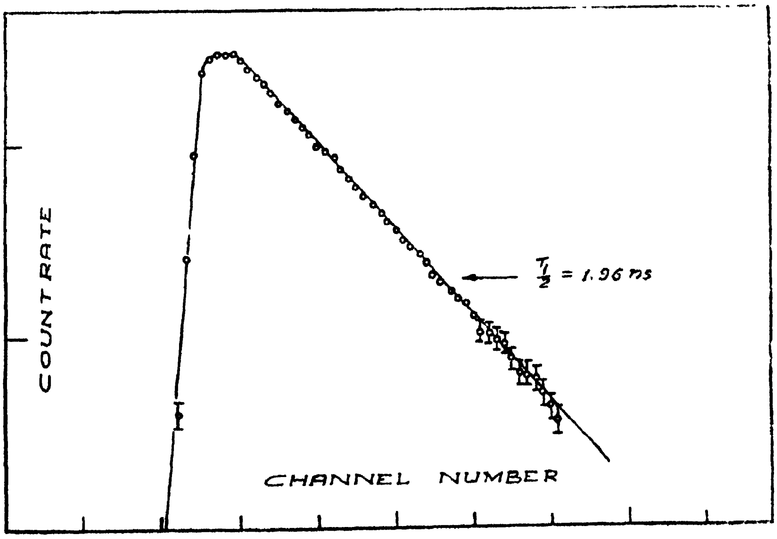

Figure 2. The time spectrum obtained with Au^{197} source. The spectrum is recorded by selecting the *K*-conversion electrons of the 191 keV transition in the early channel (differentially at 110 keV) and the *L*-conversions electrons of the 77 keV transition in the late channel (differentially at 55 keV). The slope on the right side (1·96 corresponds to the half-life of the 77 kev. state.

least-squares fitted to yield $T_{1/2}$. Five such trials are made and a value of $(1{\cdot}95 \mp 0{\cdot}06)$ *ns* is obtained as an average of these five trials. The error attached in the measurement of the half-life is the compound error which comes from the statistical error ($\sim$ 2%), the error in the calibration of the multichannel analyser ($\sim$2%) and the error in the measurement of cable lengths ($\sim$1%).

DISCUSSION

The present value of half-life of the 77 keV state is in good agreement with the results of Sunyar (1953) and Roberts and Thompson (1963), and is in disagreement with that of Nagle *et al*, (1960). The measured value of half-life is employed to estimate the $M1$ and $E2$ gamma ray transition probabilities $T(M1)$ and $T(E2)$ of the 77 keV transition using the expressions

$$T(M1) = R/\{T_{1/2} \times 1{\cdot}44 \times (1+\alpha_{tot}\} \times 1/(1+\delta^2) \qquad \dots \quad (1)$$

$$T(E2) = R/\{T_{1/2} \times 1{\cdot}44 \times (1+\alpha_{tot}\} \times \delta^2/(1+\delta^2) \qquad \dots \quad (2)$$

where R is the branching ratio (unity for the present case), α_{tot} and δ^2 are the total conversion coefficient and the mixing ratio ($E2/M1$), respectively. These values for the present case are assumed from the data of Joshi and Tosar (1960) and Reyes-Suter and Suter (1961) as $\alpha_{tot} = 3{\cdot}4$ and $\delta^2 = 0{\cdot}11 \mp 0{\cdot}02$. The values of $T(M1)$ and $T(E2)$ thus obtained are given in table 1 together with the corresponding single particle estimates. The present value of $T(E2)$ is in satisfactory agreement with the values of $T(E2)$ viz., $(1{\cdot}2 \mp 0{\cdot}4) \times 10^7$ sec^{-1} and $(9{\cdot}32^{-1.38}_{+2.66}) \times 10^6$ sec^{-1} obtained from the Coulomb excitation studies of Bernstein and Louis (1963) and McGowan and Stelson (1958), respectively. The error in $T(E2)$ is essentially due to the large error in δ^2 and the overall errors in $T(M1)$ and $T(E2)$ amount to about 6% and 20%, respectively. The error in α_{tot} is not reported and is tentatively assumed to be 5%*r*, which is usually encountered in the measurements of

Table 1

$M1$ and $E2$ Gamma-ray transition probabilities for the 77 keV transition.

Description	$T(M1)$ (sec^{-1})	$M1$ hindrance	$T(E2)$ (sec^{-1})	$E2$ enhancement
Experimental	$(7.30 \pm 0.45) \times 10^7$	—	$(8.02 \pm 1.60) \times 10^6$	—
Single particle estimate	2.65×10^{10}	(363 ± 22)	4.59×10^5	(17.5 ± 3.5)
Wavefunctions of Kisslinger and Sorensen (1963)	1.87×10^7	(3.90 ± 0.16)*	5.29×10^5	(15 ± 3)

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*Mi-enhancement.

α_{tot} of this order. The single particle estimates included in table 1 are obtained using the expressions

$$T(M1)_{S.P.} = 2{\cdot}9\times10^{13}\,E_{\gamma}{}^{3}S \tag{3}$$

$$T(E2)_{S.P.} = 7{\cdot}4\times10^{7}\,A^{4/3}\,E_{\gamma}{}^{5}S \tag{4}$$

where A is the mass number of the isotope, E is the energy of the transition in MeV and S is the statistical factor. The values of S are taken from the tables of Moszowski (1953, 1965). It can be seen from table 1, that an $M1$ hindrance of (363 ∓ 22) and an $E2$ enhancement of ($17{\cdot}5\mp3{\cdot}5$) are obtained in the present case.

The large $M1$ hindrance may be attributed to the l-forbiddenness. However, this amounts to assuming the ground and the 77 keV states to be single particle states $d_{3/2}$ and $s_{1/2}$, respectively. The value of the magnetic moment of the 77 keV state being much different from the single particle value, the excited state at 77 keV does not appear to be arising out of pure particle excitation. In order to account for the reduction in the magnetic moment and also to account for the observed $E2$ enhancement, some admixture of the collective type must be considered.

The simplest type of collective excitation is to consider the one proposed by De-Shalit (1961). However, pure De-Shalit's wavefunctions cannot be chosen for the ground and the 77 keV states in Au^{197}, inasmuch as the 77 keV transition includes $M1$ part. McKinley and Rinard, in their attempt for a simultaneous determination of core parameters, obtained the best fit for most of the experimental data with the following wavefunctions for the ground and the 77 keV states ·

$$|\tfrac{3}{2}> = 0{\cdot}85\,|0\;\tfrac{3}{2}\;\tfrac{3}{2}> +0{\cdot}53\,|2\;\tfrac{3}{2}\;\tfrac{3}{2}>$$

$$|\tfrac{1}{2}> = |2\;\tfrac{3}{2}\;\tfrac{1}{2}>$$

The values of $T(M1)$ and $T(E2)$ estimated from these wavefunctions tended towards the extreme values in the experimental range. In addition, as pointed out by Haverfield *et al*, it is not possible to account for the observed intensity of the 202 keV transition (occurring between the 279 keV and 77 keV states) unless some admixture of particle part in the 77 keV state and 1/2+phonon part in the 279 keV state are considered.

Alternatively, the model of Kisslinger and Sorensen (1963) may be considered and the values of $T(M1)$ and $T(E2)$ can be estimated from the wavefunctions furnished by them for the ground and the 77 keV states. Their wavefunctions for these states are given by

$$|\tfrac{3}{2}> = 0{\cdot}89\,|0\;\tfrac{3}{2}\;\tfrac{3}{2}> +0{\cdot}13\,|2\;\tfrac{7}{2}\;\tfrac{3}{2}> -0{\cdot}09\,|2\;\tfrac{5}{2}\;\tfrac{3}{2}> +0{\cdot}40\,|2\tfrac{3}{2}\;\tfrac{3}{2}> -0{\cdot}10\,|2\tfrac{1}{2}\tfrac{3}{2}>$$

$$|\tfrac{1}{2}> = 0{\cdot}96\,|0\tfrac{1}{2}\tfrac{1}{2}> +0{\cdot}16\,|2\tfrac{5}{2}\;\tfrac{1}{2}> +0{\cdot}19\,|2\tfrac{3}{2}\;\tfrac{1}{2}>$$

The $M1$ transition probability $T(M1)$ is estimated by considering the contributions from the 5/2+phonon and the 3/2+phonon parts of the wavefunctions, together with the contribution from those parts of the wavefunctions in which the quasi-particles coupled to the phonon are spin-orbit partners. The pure quasi-particle contribution is neglected because of l-forbiddenness. The value of $T(M1)$ is obtained, using the expression derived by Sorensen (1963), as $1{\cdot}87\times 10^7$ sec^{-1}.

The value of $T(E2)$ is likewise obtained from the above wavefunctions, by estimating the transition amplitudes of the particle part, which is considered between the pure-quasi-particle parts of both the wavefunctions, and the collective part, which is considered between the 3/2+phonon part in the 77 keV state and the quasi-particle part in the ground state and between the quasi-particle part in the 77 keV state. and the 1/2+phonon part in the ground state. The value of $T(E2)$ thus estimated, using the expression of Sorensen (1964), is given by

$$T(E2)_{est} = 5{\cdot}29\times 10^4 \text{ sec}^{-1}.$$

In the estimation of $T(E2)$, the value of $B(E2)$ for the core is assumed (Siegbahn, 1965) to be equal to the average value of $B(E2)$ for Pt^{196} and Hg^{198}. The values of $T(M1)$ and $T(E2)$ estimated from these wavefunctions are also included in table 1.

It may be noticed from table 1 that the present experimental values of $T(M1)$ and $T(E2)$ show enhancements of $(3{\cdot}90\mp 0{\cdot}16)$ and (15 ∓ 3), respectively, over the estimated values from Kisslinger and Sorensen wavefunctions. Although a considerable improvement is achieved in $T(M1)$, there is no change of situation in respect of $T(E2)$. It thus appears that the amplitudes of the different parts have to be adjusted to obtain a better fit for the experimental data. However, as a large number of parameters are involved (8 amplitudes in the two wavefunctions) this adjustment cannot be carried out uniquely. The following method is adopted in the present case.

The ground state of Au-197 is assumed to be well represented by the Kisslinger–Sorensen wavefunction, inasmuch as it consists of a large particle part, as it should be. The amplitudes in the wavefunction of the 77 keV state are therefore proposed to be adjusted to yield the best fit for the experimental values of $T(M1)$ and $T(E2)$. For this purpose the wavefunction of the 77 keV state is assumed to be given by

$$|\tfrac{1}{2}> = \sqrt{1-A^2-B^2}\,|0\tfrac{1}{2}\tfrac{1}{2}> + A\,|2\tfrac{5}{2}\,\tfrac{1}{2}> + B\,|2\tfrac{3}{2}\,\tfrac{1}{2}>$$

where A and B are constants and are to be evaluated using the present experimental values of $T(M1)$ and $T(E2)$. The $M1$ and $E2$ transition probabilities are estimated, using the Kisslinger–Sorensen (1963) wavefunction for the ground state and the above one for the 77 keV state, in terms of A and B, and then equated to the respective experimental values. The equations thus obtained are

$$0{\cdot}3833A+0{\cdot}2093B = \pm(0{\cdot}1996\pm0{\cdot}0039)$$

$$0{\cdot}0228\sqrt{1-A^2-B^2}+0{\cdot}2167B = \pm(0{\cdot}2454\pm0{\cdot}0245)$$

But no real solutions for A and B could be obtained from these equations. As a more simplifying approach, the 5/2+phonon contribution (value of A) is assumed to be represented by the value furnished in the Kisslinger–Sorensen wavefunction (i.e., 0·16) and various values of B are considered in the range 0·19 to 0·95 (0·19 being the value corresponding to Kisslinger–Sorensen wavefunction). The values of $\sqrt{1-A^2-B^2}$ are obtained for each value of B and the values of $T(M1)$ and $T(E2)$ are estimated for each set. This approach is adopted in view of the fact that the 5/2+phonon amplitude does not effect the $T(E2)$ value. On the other hand, the variation of it with the particle amplitude and 3/2+phonon amplitude is considerable. The variations of $T(M1)$ and $T(E2)$ thus obtained are shown in table 2.

Table 2

The values of $T(M1)$ and $T(E2)$ estimated for an empirical choice of amplitudes.

Sr. No.	$\sqrt{1-A^2-B^2}$	A	B	$T(M1)_{est}$ (sec^{-1})	$\frac{T(M1)_{exp}}{T(M1)_{est}}$	$T(E2)_{est}$ (sec^{-1})	$\frac{T(E2)_{exp}}{T(E2)_{est}}$
1	0.96	0.16	0.19	1.87×10^7	3.90 ± 0.16	6.28×10^5	12.77 ± 2.55
2	0.94	0.16	0.30	2.82×10^7	2.59 ± 0.10	1.13×10^6	7.10 ± 1.40
3	0.85	0.16	0.50	5.05×10^7	1.45 ± 0.06	2.35×10^6	3.41 ± 0.68
4	0.70	0.16	0.70	7.91×10^7	0.92 ± 0.04	3.92×10^6	2.05 ± 0.41
5	0.41	0.16	0.90	1.14×10^8	0.64 ± 0.03	5.69×10^6	1.41 ± 0.28
6	0.27	0.16	0.95	1.24×10^8	0.59 ± 0.02	6.08×10^6	1.32 ± 0.26

It can be seen from table 2, that the first set corresponds to the Kisslinger–Sorensen wavefunction which contains a large particle amplitude. As the contribution of the 3/2+phonon (value of B) is enhanced, the particle amplitude gets reduced. The last set in the table approaches the De-Shalit's wavefunction. The table also includes the values of ratios of the experimental and theoretical transition probabilities. For the first three sets in the table, $T(M1)$ shows an enhancement while for the last three it shows a retardation. On the other hand, the enhancement in $T(E2)$ decreases monotonically throughout. It can also be seen from the table that there exists no set in the table which can simultaneously account for $T(M1)$ and $T(E2)$. If the value of A (5/2+phonon contribution) is reduced, the estimated value of $T(E2)$ goes up, thereby bringing about better agreement with the experimental value. However, a reduction in A reduces the value of $T(M1)$ and a simultaneous fit of $T(E2)$ and $T(M1)$ therefore does not seem possible. This difficulty appears to be due to an inaccuracy in the estimation of δ. If this value is lowered, a simultaneous fit is possible. A redetermination of δ^2 is therefore worthwhile. In any case, it appears that the wavefunction of the 77 keV state should contain sizable amounts of the particle and the $3/2+$phonon amplitudes, unlike the wavefunctions of De-Shalit and Kisslinger and Sorensen, which represent the extreme viewpoints.

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