ISOMERIC CROSS-SECTION FOR THE ^{197}Au(p, n) ^{197,197m}Hg REACTION IN THE ENERGY INTERVAL 6.5–9.5 MeV

By W. Kusch

Institute of Nuclear Research, Świerk*

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Isomeric ratio in the reaction ^{197}Au(p, n) $^{197,\ 197m}$Hg, in the energy interval 6.5—9.5 MeV, was measured using the activation method. The calculations of σ_m/σ_g values, expected by statistical model, were performed as well, with the application of the scheme described by Huizenga and Vandenbosch. The best fit to the experimental data was obtained for the level density parameter $a \simeq 20$, by the fixed spin-cut-off parameter $\sigma = 4$. On the ground of the same experimental data it was possible to determine the excitation function for (p, n) reaction, which, after normalization, was compared with theoretical one.

1. Introduction

The excitation of isomeric states in nuclear reactions may be considered as one of the efficient tools of statistical model testing. For excitations corresponding to the large level densities, the isomeric ratio σ_m/σ_g, according to this model, should be nearly one. The experimental systematics of σ_m/σ_g values in general confirms this conclusion: for energy of bombarding particles exceeding slightly the reaction threshold, the σ_m/σ_g dependence on atomic number reflects the changes of excited level densities, and the isometric ratio increases from 0.6 up to 0.9, when the atomic number changes from 35 to 54.

But there are some exceptions in this systematics. As shown by Boehm et al. [1], the isomeric ratio for ^{197}Hg in (p, n) reaction, for the energy of 6.7 MeV, is four times lower than expected. In frames of extensive research program, Vandenbosch and Huizenga [2] investigated the same reaction. They measured σ_m/σ_g in the energy interval of 7.3—10.4 MeV, and interpreted the experimental data on the basis of their theoretical formalism, assuming the low density parameter $a = 6$, and the spin cut-off parameter $\sigma = 4$. Owing to the poor knowledge of the decay scheme, the decay of ^{197}Hg ground state was determined by measuring the intensity of 77 keV gamma rays. As the energy of this line coincides with that of very strong X-ray line, it needed the estimation of intensity of four components of X-ray line, resulting from the electron capture and conversion.

In this paper the results of reexamination of ^{197}Hg isomeric ratio, in the similar

* Address: Instytut Badań Jądrowych, Świerk, 05-400 Otwock, Poland.

energy interval, are presented. The gamma ray spectrum was measured with Ge(Li) detector, and transition intensities were determined using actual data on decay scheme of ^{197}Hg and ^{197}Au, and on electron conversion coefficients [3]. Our results were analysed using Huizenga and Vandenbosch method [2, 4]. The experimental data were also used for determining the (p, n) reaction excitation function in the energy range 6.5 — 9.5 MeV.

2. Experiment

The application of activation method, with the use of the Ge(Li) detector, was estimated as adequate for obtaining satisfactory accuracy of experimental results. The stack of golden and lead foils were irradiated during 10 hours by protons, accelerated in the linear

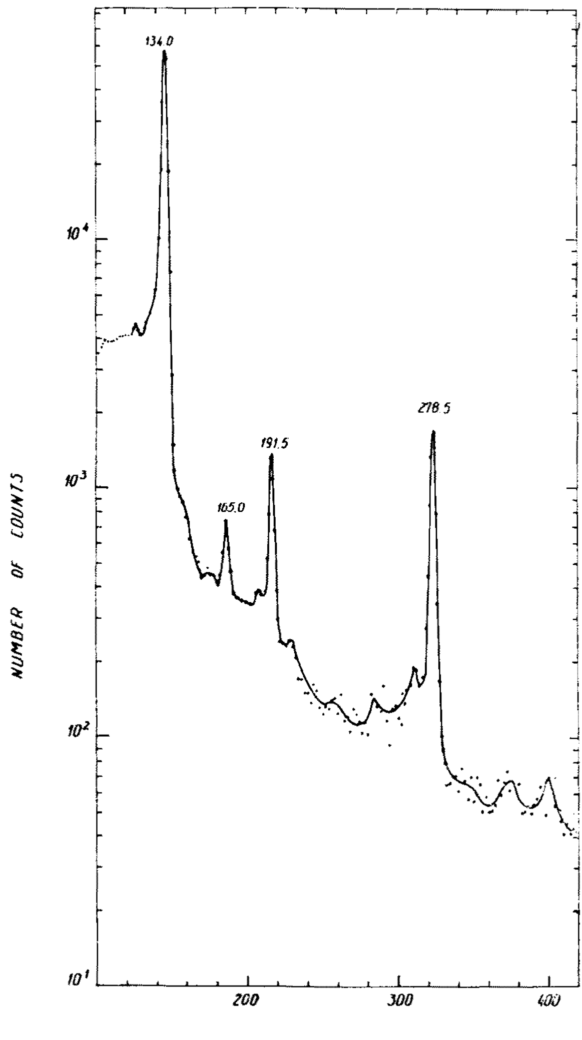

Fig. 1. Gamma ray spectrum from the decay of ^{197}Hg, produced in $^{197}Au(p, n)$ reaction

accelerator of the Institute for Nuclear Research in Świerk. The radioactivity of foils was detected afterwards in identical geometrical conditions with 23 cm^3 Ge(Li) detector of accurately determined efficiency. Several series of spectra were registered. Gamma-ray spectrum of ^{206}Pb, from the decay of ^{206}Bi, was measured for energy calibration, and for efficiency testing. The comparison of intensities of most prominent gamma-rays of our measurements with Manthuruthil's results [5] proved that our spectrum could be considered as a base for the computation of the cross section. The spectrum of irradiated gold is shown in Fig. 1. All of the strong transitions, in the energy range 100 — 540 keV, in ^{197}Au and in ^{197}Hg, were identified. As can be seen from the nuclear level scheme (Fig. 2), the gamma-ray spectrum of ^{197}Au from the decay of ^{197}Hg and ^{197m}Hg should be rather poor. The gamma-ray of 77.3 keV is hard to extract from the background of strong X-ray

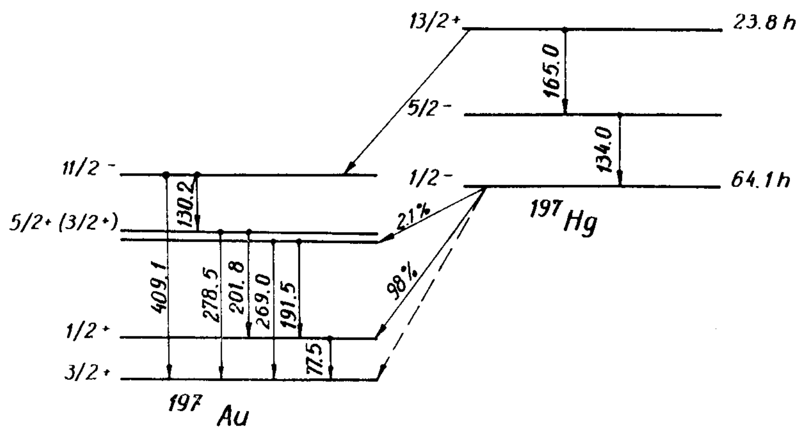

Fig. 2. Decay scheme of isomeric state and ground state of ^{197}Hg

radiation (K_{β_1}— 78.00 keV, K_{β_2}— 77.58 keV). The gamma-ray 134.0 keV represents the strongest gamma transition (E2) of the spectrum. It contains a small admixture (less than 1%) of gamma-ray 130.2 keV (E3). The intensity of 165.0 keV transition is represented mainly by conversion electrons, as the total electron conversion coefficient amounts $\alpha = 344$ (theoretical). However, the experimental data on conversion electron coefficient are uncertain, and the intensity of weak gamma-ray was not determined with satisfactory accuracy in our measurements.

The strong gamma-ray 191.5 keV (M1) is fed from the decay of ^{197}Hg in its ground state. The intensity of 278.5 keV gamma-ray was measured scrupulously, what was important for the determination of isomeric ratio. The weak gamma-rays of energy 201.8 keV, 269.2 keV and 409.1 keV, registered in our spectrum, do not play any role in following calculations.

Data on transitions in ^{197}Hg and ^{197}Au, necessary for calculations, are the gamma--ray intensities of 134.0, 191.5 and 278.9 keV transitions, and their total electron conversion coefficients. Table I presents the experimental α_k and α values, taken into account in NDS [3], and our estimation of the average α values.

TABLE I

Electron conversion coefficients of transitions in ^{197}Hg and ^{197}Au, consisting the base for isomeric ratio calculations. All data taken from NDS (1972)

TRANSITION	134 keV	191.5 keV	278.5 keV
α_k	0,5 [15]	0,9 [11] 0,65 [12] 0,77 [13] 0,78 [14] average: 0,77 ± 0,05	0,32±0,04 [17]
K:L:M:N	K/L+M=0,31 [15] K/L+M=0,37±0,02 [16]	K/L+M+N=4,3 [13] K/L+M+N=3,8 [14] average: 4,05 ± 0,25	
α	2,10 ±0,42 [15]	0,96 ± 0,10	α=0,44 ± 0,10 [17]

3. Calculation of isomeric ratio

The experimental results were analyzed using the method of Huizenga and Vandenbosch [2, 4]. The relative probability of a state J_c formation in the compound nucleus by protons of energy E_p, $P(J_c, E_p)$, can be expressed as:

$$P(J_c, E_p) \simeq \sum_{S=|J-s|}^{J+s} \sum_{l=|J_c-S|}^{J_c+S} (2J_c+1)T_l(E_p),$$

where J and s are the spins of target nucleus and proton, respectively, and $T_l(E_p)$ are the transmission coefficients [6]. The nucleus decays to the excited state J_f of the final nucleus by emitting the neutron of energy E_n and angular momentum l. The relative probability of the transition $J_c \to J_f$

$$P(J_c \to J_f, E_n) \simeq \varrho(J_f) \sum_{S=|J_f-s|}^{J_f+s} \sum_{l=|J_c-S|}^{J_c+S} T_l(E_n)$$

depends on the relative level density of the final nucleus:

$$\varrho(J_f) \simeq (2J_f+1) \exp\left[-J_f(2J_f+1)/2\sigma^2\right],$$

where $T_l(E_n)$ are the neutron transmission coefficients, and σ is spin-cut-off parameter. As shown by Vandenbosch and Huizenga [2], the neutron energy spectrum can be replaced in the calculation by the mean neutron given by evaporation theory. The relative probability of the formation of a final nucleus with a spin J_f is:

$$P(J_f) = \sum_{J_c} P(J_c, E_p)P(J_c \to J_{f'}, E_n).$$

It is assumed that the neutron emission is followed by dipole gamma-ray cascade with the average number of gamma-rays given by the formula ([7])

$$N_\gamma = \frac{1}{1+l}(aE_{exc})^{1/2}.$$

The spin distribution, after the emission of each of the successive gamma-ray, can be easily calculated in the approximation that the transition $J_f \to J_{f'}$ depens only on the level density of the final states. Fig. 3 presents the results of such calculations for the

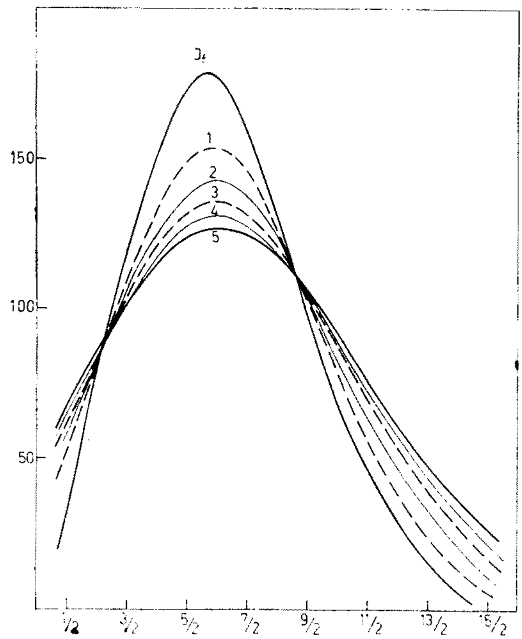

Fig. 3. Angular momentum distribution of ^{197}Hg final state J_f, after emission of the neutron, and angular momentum distributions of states populated by the dipole gamma ray cascade. The numbers refer to the succeeding transitions

energy of bombarding protons $E_p = 10$ MeV, and statistical model parameters $\sigma = 4$, and $a = 18$.

It was assumed that after the emission of $N-1$ gamma-rays of dipole radiation, the last gamma-ray ought to feed isomeric state, or ground (eventual first excited) state.

The isomeric ratios were calculated with those approximations for the $E_p = 7.0$ MeV and 10 MeV, and statistical model parameters $\sigma = 4$ and $a = 8$, 18, and 44.

4. *Results*

The gamma-ray spectra of two series of irradiation were used for determination of isomeric ratios, and for determination of (p, n) reaction excitation function in the energy interval 6.5 — 9.5 MeV.

A. The intensity ratio of transitions 134.0 and 278.9 keV is directly related to the decay probability ratio of ^{197}Hg isomeric state by electron capture, or by gamma-ray emission. This value, important in the calculation of isomeric ratio, was determined by several groups, but the dispersion of results was rather large. Although the intensity of both gamma-rays was determined precisely in our experiment, the error of branching ratio includes errors of electron conversion coefficients which are remarkable. Finally, our result is: $k = 0.055 \pm 0.004$.

B. Numerous excited states of final nucleus, fed in the considered (p, n) reaction, decay by means of isomeric state (1), or directly to the ground state (2). In the considered case both of them are unstable (Λ_1, Λ_2).

As has been shown [18], the relation between the transition intensities from states (1) and (2), and the isomeric ratio, may be expressed in the following way:

$$\sigma_2/\sigma_1 = XDU - \gamma_a DU + \gamma_b,$$

where, in our case, $X = [I^{\gamma}_{191}(1+\alpha_{191})k]/[I_{134}(1+\alpha_{134})m]$, k and m denote the branching ratio for the decay of isomeric state and of the ground state to the 269 keV state of ^{197}Au, respectively (Fig. 2), $D = (1-e^{-\Lambda_1\tau})/(1-e^{-\Lambda_2\tau})$ where τ is the irradiation time, $U = \exp(\Delta\Lambda t)$, where $\Delta\Lambda = \Lambda_2 - \Lambda_1$, t is the time registered from the moment of the irradiation stoped, $\gamma_a = k\dfrac{\Lambda_1}{\Lambda_1 - \Lambda_2}$, and $\gamma_b = k\dfrac{\Lambda_2}{\Lambda_1 - \Lambda_2}$.

Using the above formula, as well as the electron conversion values (Table I), we were able to determine the isomeric ratio in the proton energy interval 6.5–9.5 MeV. Fig. 4 presents our results of two series: one point, at the energy 6.7 MeV, as measured

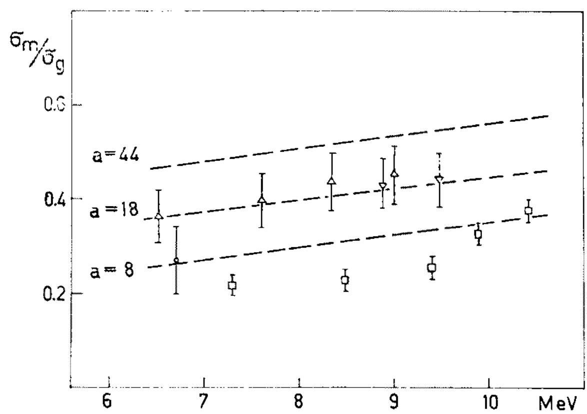

Fig. 4. Isomeric cross-section for the ^{197}Au(p, n) $^{197, 197m}$Hg reaction in the energy interval 6.5—10.4 MeV, △, ▽ — results of this experiment, □ — data given by Vandenbosch and Huizenga [2], ○ — the point at 6.7 MeV, measured by Boehm et al. [1]. The doted lines present the result of our calculations

by Boehm et al. [1], and the results presented by Vandenbosch and Huizenga [2]. The errors of particular parameters of our formula were the following: $\Delta D/D = 0.030$; $\Delta U/U = 0.001$; $\Delta\gamma_a/\gamma_a = 0.008$; $\Delta\gamma_b/\gamma_b = 0.013$, and $\Delta X/X = 0.15$. As can be seen, the main contribution to the isomeric ratio error (18%) comes from transition intensity ratio, including electron conversion coefficients. Dashed lines, drawn on the figure, are carried through the points calculated according to the scheme outlined in the previous section for spin cut-off parameter $\sigma = 4$, level density parameter $a = 8$, 18, and 44, and for proton energy 7 and 10 MeV. Theoretical line for $a = 18$ fits reasonably well our experimental data.

C. The knowledge of isomeric ratio for (p, n) reaction enables us to construct, in easy way, the (p, n) reaction excitation function in the same energy interval. The calculated

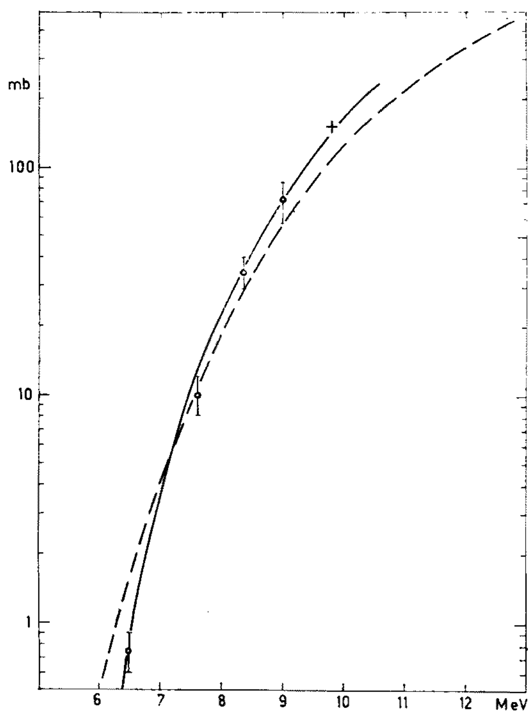

Fig. 5. The total reaction cross-section (doted line), calculated by Mani et al. [6], the experimental point at 9.85 MeV, given by Albert and Hansen [8], and our results, normalized to this point

points, as shown in Fig. 5, are compared with theoretical curve for σ_{tot}, as given by Mani et al. [6]. Our points were normalized to the experimental results at 9.8 MeV, obtained by Albert and Hansen [8].

5. *Discussion*

Fig. 4 proves that: a) our experimental values of σ_m/σ_g are 50—75% higher than those of Vandenbosch and Huizenga; b) the energy dependence of theoretical results properly reflects the experimental data; c) the isomeric ratio, calculated with $\sigma = 4$ and $a = 18$, fits satisfactorily the experimental results.

In the first stage of calculation, the $P(J_c, E_p)$ function does not depend on statistical model parameter a. The distribution function for the angular momentum, after the neutron emission, was obtained using the approximation $E_n = 2T$, which means the introduction of level density parameter. But the shapes of $P(J_c \to J_f, E_n)$ and $P(J_f)$ functions appeared to be only slightly dependent on the a value. Nuclear level density reveals its role in the last stage of calculations because the number of gamma-rays in the cascade, N_γ, is the function of the a parameter, and therefore the application of precise formula for N_γ is of great importance. The dependence of level density parameter on atomic number shows minima at magic numbers [9], but for $A = 197$ our value of $a \simeq 20$ is consistent with this systematics. One can conclude that the low value of isomeric ratio for ^{197}Hg obtained in our measurement (but higher than those obtained in [1] and [2]) may be reasonably interpreted in frames of statistical model.

In the energy region extending from about 1 MeV above the threshold to several MeV above the Coulomb barrier height, the (p, n) reaction cross section can be considered as a measure of the cross section for compound nucleus formation [10]. The energy interval of our experiment does fulfil this requirement. As shown on Fig. 5, the experimental curve is slightly steeper than the theoretical one [6], what may be interpreted as non--statistical mechanism contribution.

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REFERENCES

[1] F. Boehm, P. Marimier, P. Preiswerk, *Helv. Phys. Acta* **25**, 599 (1952).
[2] R. Vandenbosch, J. R. Huizenga, *Phys. Rev.* **120**, 1313 (1960).
[3] *Nuclear Data Sheets*, 7, N2, 1972.
[4] J. R. Huizenga, R. Vandenbosch, *Phys. Rev.* **120**, 1305 (1960).
[5] J. C. Manthuruthil, D. C. Camp, A. V. Ramayya, J. H. Hamilton, J. J. Pinajian, J. W. Doornebos, *Phys. Rev.* **C6**, 1870 (1972).
[6] G. S. Mani, M. A. Melkanoff, I. Iori, *Report C. E. A.*, N2379, 1963.
[7] V. M. Strutinski, L. V. Groshev, M. K. Akimova, *Nucl. Phys.* **16**, 657 (1960).
[8] R. D. Albert, L. F. Hansen, *Phys. Rev.* **123**, 1749 (1961).
[9] D. Bodansky, *Ann. Rev. Nucl. Sci.* **12**, 79 (1962).
[10] M. M. Shapiro, *Phys. Rev.* **90**, 171 (1953).
[11] K. Jolly, *Helv. Phys. Acta* **28**, 403 (1955).
[12] A. Teuvrains, *Ann. Phys.* **5**, 181 (1960).
[13] R. G. Helmer, L. D. Isaak, *Phys. Rev.* **137**, B223 (1965).
[14] C. Bartlett, *Bull. Am. Phys. Soc.* 12 N1, 37BG15 (1967).
[15] O. Huber, *Helv. Phys. Acta* **24**, 127 (1951).
[16] I. J. van Heerden et al., *Nuovo Cimento* **11**, 167 (1959).
[17] F. Smend et al., *Z. Phys.* **191**, 1 (1966).
[18] W. Kusch, *INR Report* 1496/I/PL/A, Świerk 1974.