Spin of the 1029-keV Level in Hg^{200}*

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(Received 1 July 1968)

A search for 1029-keV photons following the decay of Tl^{200} has been made. These have been observed with a relative intensity $I_{1029}/I_{661}=0.049\pm0.016$. The spin assignment to the 1029-keV level of Hg^{200} is discussed.

INTRODUCTION

THE spin assignment to the 1029-keV level in Hg^{200} has been uncertain because of contradictory experimental results. Based on their internal conversion electron measurements, Sakai *et al.*[1,2] concluded that the spin-parity of this level is 2^+. Maier *et al.*[3] and Schult *et al.*[4], basing their arguments on the apparent absence of a 1029-keV γ-ray transition, conclude that the spin-parity is 0^+. In an attempt to resolve this ambiguity, a search for the 1029-keV γ-ray transition was undertaken.

EXPERIMENTAL PROCEDURE

Thallium isotopes were formed in a spallation reaction by bombarding a lead target with 3-GeV protons from the Princeton-Pennsylvania Accelerator.[5,6] The lead target was placed in the ion source of the Princeton electromagnetic isotope separator, and the volatile products were mass-dispersed. The Tl^{200} fraction was collected on an aluminum foil which served as a spectroscopy source. Several such sources were prepared.

The spectrum of γ-rays accompanying the decay of the Tl^{200} sources was obtained with an $\sim$20 cc Ge(Li) detector, at an energy resolution of $\sim$4 keV, FWHM. Each such spectrum was obtained with the source on a line from the approximate center of the detector and perpendicular to its face. Because of the low intensity of the possible 1029-keV transition, it was possible that an observed peak might arise from summing within the detector of the relatively intense 661- and 368-keV transitions. In order to investigate this possibility, four Tl^{200} γ-ray spectra were obtained under different conditions of geometry and count rate.

The count rates in the detector were carefully measured before obtaining each of the energy spectra. The solid angles subtended by the detector were determined for two of the experiments by measurement of the source-to-detector distance, and the ratio of solid angles was determined for the other two experiments from the detector counting rates and the time difference between the measurements. Peak areas were determined by simply adding the counts in each peak channel and subtracting the contribution from the continuous spectrum beneath them. This latter was determined by least-square fitting the continuous distribution on both sides of the peak.

In general, two types of summation processes are possible and are treated here.

Let $N(t)$ be the number of γ-rays emitted per second per steradian, I_i the fraction that are of energy i, ϵ_i the detector efficiency for energy i, and Ω the solid angle subtended by the detector. Then, the expected number of photons of energy i detected within the time period dt is

$$P_s(\gamma_i)\,dt=N(t)\,dtI_i\epsilon_i\int d\Omega=N(t)\,dtI_i\epsilon_i\Omega. \quad (1)$$

The expected number of random summation events, i.e., those in which γ_i and γ_j are emitted by different nuclei, is

$$\begin{aligned}P_r(\gamma_i+\gamma_j)\,dt&=P(\gamma_i)\,dt\int_{t-\tau/2}^{t+\tau/2}P(\gamma_j)\,dt'\\&=N(t)\,dtI_i\epsilon_i\int_{t-\tau/2}^{t+\tau/2}N(t')I_j\epsilon_j\,dt'\\&=N^2(t)\,dtI_i\epsilon_if_j\epsilon_j\Omega^2\tau,\end{aligned} \quad (2)$$

in which τ is the system-resolving time.

The expected number of correlated summation events, i.e., those in which γ_i and γ_j are emitted in cascade from the same nucleus with γ_i being the first

* Work supported by the U.S. Atomic Energy Commission.

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transition, is

$$P_c(\gamma_i+\gamma_j)\,dt=P(\gamma_i)\,dtP(\Omega)\epsilon_j, \quad (3)$$

$P(\Omega)$ being the probability that γ_i and γ_j are both emitted into the same solid angle, Ω. Equation (3) then becomes

$$P_c(\gamma_i+\gamma_j)\,dt=N(t)\,dtI_i\epsilon_i\epsilon_j\int d\Omega_i\int d\Omega_j W(\theta_{ij}), \quad (4)$$

with $W(\theta_{ij})$ representing the angular correlation. Under the assumption that the solid angle is small, and that therefore the angular correlation is approximately constant over Ω, Eq. (4) becomes

$$P_c(\gamma_i+\gamma_j)\,dt=N(t)\,dtI_i\epsilon_i\epsilon_j W(0)\Omega^2. \quad (5)$$

In general, an observed peak is a sum of the three possible types of events:

$$P_{\text{tot}}(\gamma_k)\,dt=[P_s(\gamma_k)+P_r(\gamma_i+\gamma_j)+P_c(\gamma_i+\gamma_j)]\,dt. \quad (6)$$

Integrating over the time period T during which a spectrum is obtained, the total number of events is

$$\begin{aligned}P_{\text{tot}}(\gamma_k)\,dt\equiv A_p(k) &= N(0)I_k\epsilon_k\Omega(1/\lambda)[1-\exp(-\lambda T)]\\ &+N^2(0)\tau I_i\epsilon_i I_j\epsilon_j\Omega^2(1/2\lambda)[1-\exp(-2\lambda T)]\\ &+N(0)I_i\epsilon_i\epsilon_j W(0)\Omega^2(1/\lambda)[1-\exp(-\lambda T)]. \quad (7)\end{aligned}$$

For the present case, $i=661$, $j=368$, and $k=1029$.

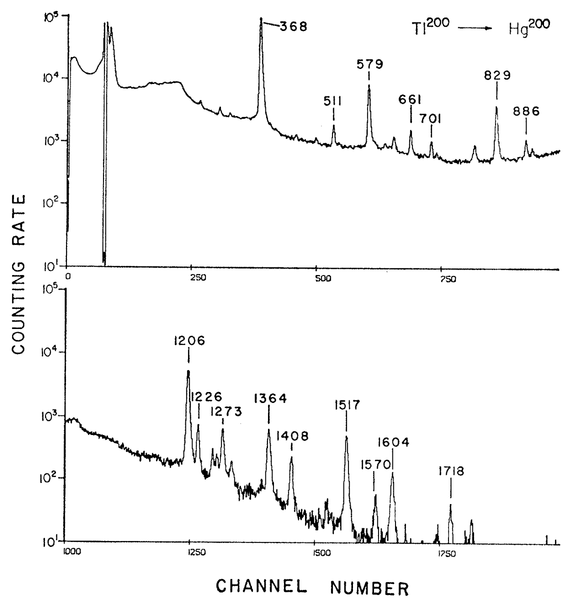

FIG. 1. The γ-ray spectrum of ^{200}Tl. Several of the more prominent lines are labeled for easy comparison to the results of Sakai, Ref. 4.

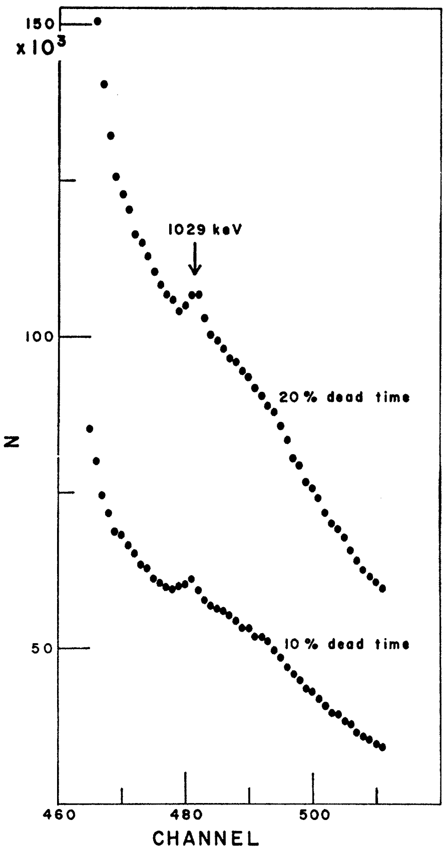

FIG. 2. The portion of the Tl^{200} γ-ray spectrum in the vicinity of 1029 keV obtained at two different count rates.

We define the peak intensity relative to the 661-keV peak:

$$\begin{aligned}R(1029) &= A_p(1029)/A(661)\\ &= A_p(1029)/N(0)I_{661}\epsilon_{661}\Omega(1/\lambda)[1-\exp(-\lambda T)]\\ &= I_{1029}\epsilon_{1029}/I_{661}\epsilon_{661}\\ &\quad +N(0)\tau I_{368}\epsilon_{368}\Omega(1/2)\\ &\quad \times[1-\exp(-2\lambda T)]/[1-\exp(-\lambda T)]\\ &\quad +\epsilon_{368}W(0)\Omega. \quad (8)\end{aligned}$$

Define $I_{1029}\epsilon_{1029}/I_{661}\epsilon_{661}=R_s(1029)$. Noting that

$$A(368)=N(0)I_{368}\Omega(1/\lambda)[1-\exp(-\lambda T)]=cA(661)$$

and substituting into Eq. (8), we obtain

$$\begin{aligned}R(1029) &= R_s(1029)\\ &+\tau(\lambda/2)\{[1+\exp(-\lambda T)]/[1-\exp(-\lambda T)]\}cA(661)\\ &+\epsilon_{368}E(0)\Omega. \quad (9)\end{aligned}$$

This can then be fitted to the data to obtain the quantities of interest.

TABLE I. Experimental conditions and results.

Run	Initial count rate[a]	Ω_i	T	$A_p^{(i)}(1029)$	$A_i(661)$
1	(487 816±720)/(5 min)	~0.1 sr	50 h	13 705±911	441 547±1 304
2	(244 952±508)/(5 min)	(1.91±0.02)Ω_1	50 h	7 999±841	232 735±939
3	(150 181±407)/(5 min)	0.216±0.009 sr	51 h	5 794±629	166 624±993
4	(150 188±396)/(5 min)	1.11±0.10 sr	51 h	7 208±653	167 566±1 038

[a] See text.

RESULTS

A Tl^{200} γ-ray spectrum taken for a relatively short time period is shown in Fig. 1, and is in good agreement with that obtained by Sakai.[2] A very weak 1029-keV peak appears in spectra, Fig. 2, taken for a much longer time period. We assign this peak to the $Tl^{200}\rightarrow Hg^{200}$ decay for the following reasons: (1) its energy is determined to be 1028.8±0.9 keV; (2) it decays with a half-life of approximately 1 day; (3) this peak does not appear in the spectrum of the neighboring mass numbers; and (4) no transitions of energy greater than 605 keV have been observed in the decay of Pb^{200}.

The experimental conditions and results for the four final experiments are shown in Table I. The only quantity requiring explanation is the one labeled initial count rate. This represents the total detector counts above a fixed lower level. This level for the first two runs is different from that for the last two runs.

Fitting Eq. (9) to this data with R_s, τ, $W(0)$, and $W(0)\Omega_1$ as parameters, we obtain

$$R_s = I_{1029}\epsilon_{1029}/I_{661}\epsilon_{661} = (3.5\pm1.1)\times10^{-2}.$$

Then, since $\epsilon_{1029}/\epsilon_{661} = 0.71\pm0.02$, we obtain for the relative intensity

$$I_{1029}/I_{661} = (4.9\pm1.6)\times10^{-2}.$$

In order to check on the validity of the approximation, Eq. (5), we estimate the values of the integral in Eq. (4) for each of the four experiments. This is accomplished by assuming a circular detector with a point source on the detector axis. The integrals are thus estimated to be in the ratios

$$1.33\Omega_1^2 : 2.39\Omega_1\Omega_2 : 1.25\Omega_3^2 : 1.10\Omega_4^2.$$

Substituting this into Eq. (9) and fitting it to the data, we obtain a value for R_s which is within 1% of that quoted above.

DISCUSSION

The results of this experiment establish the existence of a 1029-keV γ-ray transition, and therefore preclude the assignment of spin/parity 0^+. Attempting to establish this spin is, however, complicated by inconsistencies in the reported experimental results. From the results of Sakai,[2] we obtain for the ratio of K-conversion-electron intensities,

$$I_e(1029)/I_e(661) = (3.50\pm0.65)\times10^{-2},$$

and taking a weighted average of his values, we obtain for the K-conversion coefficient

$$\alpha_K(661) = (1.92\pm0.12)\times10^{-2}.$$

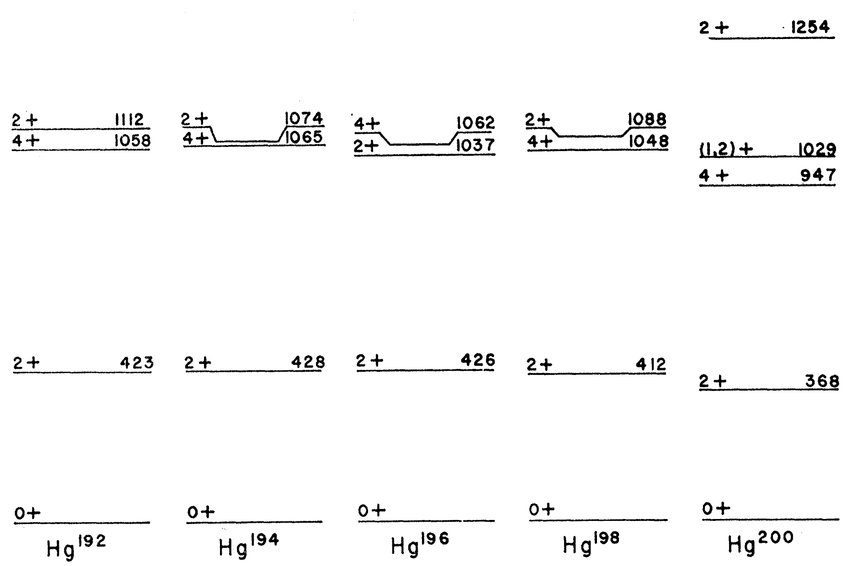

FIG. 3. Partial level schemes for $Hg^{192,194,196,198,200}$.

Using these values of Sakai and our γ-ray intensity ratio, we obtain

$$\alpha_K{}^{\text{expt}}(1029) = (1.36\pm0.52)\times10^{-2}.$$

On the other hand, Schult *et al.*[7] report

$$I_e(1029)/I_e(661) > 3.2\times10^{-2}$$

and

$$\alpha_K(661) = (1.04)\pm0.13)\times10^{-2}.$$

These results then lead to a value

$$\alpha_K{}^{\text{expt}}(1029) \lesssim (0.68\pm0.27)\times10^{-2}.$$

Since

$$\alpha_K{}^{\text{theor}}(E2,1029)\approx0.42\times10^{-2}$$

and

$$\alpha_K{}^{\text{theor}}(M1,1029)\approx1.08\times10^{-2},$$

the experimental conversion coefficient computed from Sakai's values would lead to a spin assignment of 1, whereas that obtained with the results of Schult *et al.* would yield a spin of 2.

[7] O. W. B. Schult, W. Kaiser, W. Mampe, and T. V. Egildy (private communication).

The low-lying states of the even-even mercury isotopes are shown in Fig. 3. Although the Hg^{200} state at 1254 keV may be the one corresponding to the second 2^+ states in the other isotopes, it would appear that a spin assignment of 2 to the 1029-keV level would be more consistent with the systematic trend observed.[5] Furthermore, a spin-1 state at this position would be rather difficult to understand on the basis of the applicable theoretical models. Therefore, we would favor a spin/parity assignment of 2^+ to the 1029-keV level. However, an unequivocal assignment requires a resolution of the inconsistency in the 661-keV conversion coefficient measurements.

ACKNOWLEDGMENTS

We are grateful to Professor Ben Mottelson for communicating Sakai's results to us, and to Fred. W. Loeser for his skillful operation of the isotope separator.

PHYSICAL REVIEW VOLUME 177, NUMBER 4 20 JANUARY 1969

Delayed Neutron Emission in the Decays of Short-Lived Separated Isotopes of Gaseous Fission Products*

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(Received 27 June 1968)

Delayed-neutron activity of separated isotopes of krypton and xenon and their decay products has been studied. The TRISTAN on-line isotope separator system at the Ames Laboratory Research Reactor was used to provide sources of short-lived gaseous fission products of selected masses, through $A=93$ for krypton and $A=142$ for xenon. Total delayed-neutron yields for each mass were measured by a calibrated long counter, and the relative yields of the parent and daughter nuclei in an isobaric decay chain were determined by multiscaling the delayed-neutron activity and resolving the contributions for different half-lives. The precusors and delayed neutron emission probabilities determined in this study are Kr^{92}, 0.040%; Rb^{92}, 0.012%; Kr^{93}, 2.60%; Rb^{93}, 1.65%; Xe^{141}, 0.054%; Cs^{141}, 0.073%; Xe^{142}, 0.45%; and Cs^{142}, 0.27%. A comparison is made between predictions for delayed-neutron emission from several semiempirical mass formulas and observations for isotopes of As, Br, Kr, Rb, Sb, I, Xe, and Cs.

INTRODUCTION

THE first evidence for the emission of delayed neutrons in fission was reported by Roberts *et al.*[1] shortly after the discovery of nuclear fission. The mechanism for this process, originally proposed by Bohr and Wheeler,[2] is shown in Fig. 1. If the neutron separation energy of nuclide Y^A is less than the energy available in the β decay of its parent X^A, excited states of Y^A may be populated which can decay by neutron emission instead of electromagnetic transitions. In cases where delayed neutron emission is energetically possible, the selection rules for β decay will determine the neutron yield. The neutron activity has a half-life determined by the β decay of nuclide X^A, called the precursor.

The energetics of this process favor nuclides with a few neutrons beyond a filled shell, for which the neutron separation energy is relatively low. The known fission-product delayed-neutron precursors have this neutron structure.[3] Sufficiently heavy isotopes of most elements should exhibit delayed-neutron emission since, as neutrons are added to the nucleus, the trend is for β-decay energies to increase and neutron separation energies to decrease. The systematic variation of these energies with changes in Z and A for the nuclides with

* Work performed in the Ames Laboratory of the U.S. Atomic Energy Commission. Contribution No. 2353.

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