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Gravitational Effect on Internal Conversion

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A simple model to estimate the effect of gravitational field produced by an ultracentrifuge on internal-conversion process of radioactive nuclide is presented. The calculation has been made for the 2.17-keV E3 transition of ^{99m}Tc. The possibility for experimental detection of this effect is discussed.

KEY WORDS: Gravitational field / Nuclear decay constant / Internal conversion coefficient /

I. INTRODUCTION

It is well known that the extranuclear fields produced by environmental effects, such as chemical bonding and high pressure, influence the rate of decay of radioactive nuclides.[1] However, the gravitational force is generally believed to be too small to cause any appreciable change in decay constant. According to the principle of equivalence, the gravitational forces are equivalent to the centrifugal forces in all local experiments. In 1919, Rutherford and Compton[2] suggested that the decay constant might depend on the gravitational fields and tried to detect the change in the rate of γ transitions for the radioactive source subjected to high centrifugal acceleration. Up to the present several experiments have been performed for β decays and γ transitions, but all of them failed to find any measurable effect.[3] These results can be understood from the fact that the centrifugal forces used in the experiments are not enough to change the nuclear states.

If we consider the nuclear transitions involving orbital electrons, the nuclear decay rate changes through the change in the electronic states in the atom. Generally, electronic states can be influenced by the extranuclear fields more easily than nuclear states. This fact means that the change in decay constant for internal conversion is larger than that for β decay.

It is the purpose of the present work to estimate the order of magnitude of the change in decay constant for internal conversion due to gravitational (centrifugal) fields and study the possibility for experimental detection of the gravitational effect.

II. THEORETICAL MODEL

Let us consider an atomic nucleus of mass M rotating with the angular velocity ω. The energy obtained by the nucleus can be written as

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$$\Delta E = \frac{1}{2} M R^2 \omega^2, \tag{1}$$

where R is the distance between the nucleus and the axis of rotation. When we consider an orbital electron bound to this nucleus, the electron rotates with the nucleus and also obtains the energy which is written in similar expression to Eq. (1). However, this energy is negligibly small in comparison with the energy given by Eq. (1) because of the smallness of the electron rest mass.

This fact means that the atom as a whole receives the energy of Eq. (1). Since the atomic radius is much smaller than the radius of the rotor, R, the increase in the potential energy is considered to be constant everywhere in the atom. In this case, the wave equation for the atomic electrons in the centrifugal field is expressed in the similar form to that for ordinary atom in the rest frame, except for the potential term which is increased by ΔE.

When a constant term is added to the atomic potential, the wave function is unchanged and the energy eigenvalue is shifted by the amount corresponding to the constant value. Thus, in the present model the electronic wave function is unchanged by centrifugal acceleration and only the binding energy of the orbital electron is increased by the amount given by Eq. (1) toward a positive value.

For electric 2^L-pole transition, the internal conversion coefficient is approximately written by[4)]

$$\alpha = 16\pi e^2 \frac{L}{L+1} |\psi(0)|^2 W \frac{p^{2L-3}}{k^{2L+1}}, \tag{2}$$

where e is the elementary charge, $\psi(0)$ is the electronic wave function at the nuclear surface, k denotes the nuclear transition energy, and W and p are the total energy and the momentum of the conversion electron, respectively.

When the transition energy is small, we can approximate $W \simeq 1$. There is no change in the wave function and the nuclear transition energy when the centrifugal field is present, as pointed out above. If we assume the internal conversion is only possible channel of the nuclear decay, the fractional change in the decay constant with high centrifugal acceleration is written by

$$\frac{\Delta\lambda}{\lambda} = \frac{(E+\Delta E)^{2L-3} - E^{2L-3}}{E^{2L-3}}, \tag{3}$$

where E is the kinetic energy of the conversion electron.

Substituting Eq. (1) into Eq. (3) and using $E \gg \Delta E$, we obtain

$$\frac{\Delta\lambda}{\lambda} = \left(L - \frac{3}{2}\right) \frac{MR^2\omega^2}{2E}. \tag{4}$$

By the use of rotation per unit time, n, the angular velocity is expressed as $\omega = 2\pi\, n$. Then Eq. (4) can be written as

$$\frac{\Delta\lambda}{\lambda} = 2.06 \times 10^{-14} \left(L - \frac{3}{2}\right) MR^2 n^2 / E, \tag{5}$$

where R is in cm, n in rev/s, and E in keV.

III. RESULTS AND DISCUSSION

The most interesting example to demonstrate the gravitational effect on internal conversion is ^{99m}Tc. This isomer is the second excited state of ^{99}Tc and decays to the first excited state by the 2.17-keV E3 transition with a half life of 6.0 h. The latter state immediately cascades down to the ground state through emission of 140.5-keV γ rays. The isomeric transition of ^{99m}Tc is strongly converted and $\Delta\lambda/\lambda$ is considered to be expressed by Eq. (5).

Owing to the low transition energy, only electrons from M, N, and O shells can be ejected by the conversion process. No experimental values have been reported for the relative ratios of N-subshell conversion coefficients in ^{99}Tc. In the present work, we used the recently published tables calculated by Rösel *et al.*[5] and evaluated the relative intensities for all M- and N-subshell conversion coefficients at 2.17 keV. Contributions from O shell are negligibly small. By the use of conversion coefficients thus obtained, we calculated the fractional change of the decay constant in ^{99m}Tc.

In Fig. 1 is shown the calculated values for $\Delta\lambda/\lambda$ of ^{99m}Tc as a function of n. The radius of the rotor on which the radioactive nuclide is deposited is taken to be R=0.119 cm. As can be seen from Eq. (5), $\Delta\lambda/\lambda$ is proportional to n^2.

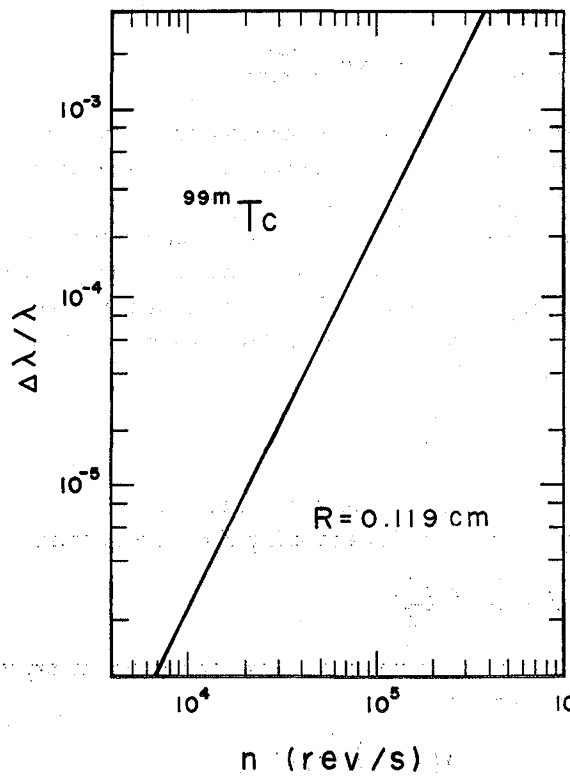

Fig. 1. The fractional change in the decay constant of ^{99m}Tc as a function of n for R=0.119 cm.

The recent measuring system for relative change in decay constant can detect $\Delta\lambda/\lambda$ in order of magnitude of 10^{-5}. For example, it can be seen from Fig. 1 that for $R=0.119$ cm and for $n=6\times10^4$ rev/s, $\Delta\lambda/\lambda$ is 8.57×10^{-5}. On the other hand, in our laboratory we succeeded to obtain the high centrifugal field up to 8.45×10^7 g for $R=0.119$ cm.[6] This corresponds to $n=1.3\times10^5$ rev/s. From these facts, we can say that the gravitational effect on internal conversion is measurable with the modern experimental apparatus.

Up to the present, only one experimental attempt to detect influence of the gravitational field on internal conversion has been reported. Freed *et al.*[7] tried to measure the change in the decay rate of ^{67}Ga, ^{69}Zn, and ^{115m}In. The centrifugal fields obtained by them are too small, less than 10^6 g, to observe the gravitational effect. For example, in the case of the 93.3-keV E2 transition of ^{67}Ga, the fractional change in the rate of internal conversion is $\Delta\alpha/\alpha=2\times10^{-7}$ for $R=0.872$ cm and $n=5100$ rev/s. This value is by two order of magnitude smaller than the measurable limit. Furthermore, the K-shell conversion coefficient of this transition is 0.63. We can assume no effect in the γ-ray transition rate. Taking into account this γ-ray decay channel, the fractional change in the decay constant, $\Delta\lambda/\lambda$, becomes much smaller.

In conclusion, the effect of gravitational fields on the rate of internal conversion has been estimated in a simple model. The result indicates that the effect is measurable by the use of modern techniques to measure small change in decay rate with high accuracy and the ultracentrifugal fields recently attained. The experimental search for the effect of gravitational field on the nuclear decay of ^{99m}Tc is now in progress in our laboratory.

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