Can Nuclear Decay constant be Modified?

Il-Tong Cheon

Department of Physics, Yonsei University, Seoul 120 – 749, Korea

Abstract

The life-time of $^{133}$Cs in the first excited state has been measured with the Mössbauer method by placing the absorber, CsCl, between two parallel flat plates and the gamma-ray source, Ba$^*TiO_3$, in the free space. The result is 9.37±0.19 ns, which is 49 percent larger than the standard value 6.27±0.02 ns.

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I. INTRODUCTION

Recently, a series of investigations were carried out on the effect of vacuum fluctuation on nuclear energy levels[1-4]. These works explored energy level shifts due to vacuum fluctuations in a finite space. In addition, it was reported that the life-time of the hydrogen 2P-state could change by about 3~5 percent, if the atom was placed between two parallel conducting plates separated from each other by 1µm [5]. There are another reports that spontaneous emissions by a Rydberg atom [6] and those of cyclotron radiation [7] can be inhibited by cavity effects. There are also some attempts to observe changes of decay constants with technetium (see Table 1).

This letter will report an experimental result that the life-time of a radioactive nucleus put between two parallel flat plates becomes longer than that of the nucleus in free space. To date, the life-time of a nucleus has been believed to be an invariable quantity. Namely, it has been supposed that even if electric or magnetic field were applied, nuclear energy level widths would remain unchanged, although shifts or splitting could take place. Notice that the life-time is proportional to the inverse of the energy level width.

II. EXPERIMENT

In order to explore the shift of nuclear life-time, we carried out Mössbauer measurement of the width of the first excited state in the $^{133}$Cs nucleus using the facilities at Leuven University.

A. Gamma-ray source

The compound $Ba^*TiO_3$ was manufactured as the gamma-ray source. The manufacturing process is as follows: A mixture of $Ba^*Cl_2$, $BaCO_3$ and $TiO_2$ in the ratio of 1:3:4 was pulverized and heated at 1200°C for 20 hours in an electric oven followed by annealing at 700~800°C for two days. Since it was not sufficiently hard at this stage, we pulverized
it again and, then, heated once more at 1200°C for 40 hours. X-ray diffraction analysis showed a characteristic $BaTiO_3$ compound pattern and confirmed this sample to be a good gamma-ray source.

**B. Measurement without plates**

The source in 2.4mCi amount was fixed to the electromechanical spectrometer providing the Doppler velocity. The result obtained with the scintillation counter showed indeed a typical Mössbauer spectrum of a single line. This spectrum was obtained at 4.2K by using $CsCl$ powder with 300$mg/cm^2$ thickness as the absorber. Its volume density was 4$g/cm^3$, namely 300$mg Csl$ in a volume $1cm \times 1cm \times 0.75mm$. The line broadening is 0.71$mm/s$ and the relative depth of the spectrum is around 1.3 percent. The spectrum corresponds to an 81KeV gamma-ray emitted by the transition from the first excited state $^{5/2} +$ to the ground state $^{7/2} +$ of $^{133}Cs$. The reduced $\chi$-square of the Lorentzian spectrum between 6 and 251 channels was 1.3, and the relative error for line position is around 2%. The width at the half-height of the Mössbauer spectrum was $\Gamma_{exp} = 0.796 \pm 0.014mm/s$, equivalently $\Gamma_{exp} = (2.149 \pm 0.038) \times 10^{-7}eV$. This value contains a thickness effect[8] of the absorber and possible unresolved hyperfine interaction arising from distortions in the $BaTiO_3$ lattice and a possible experimental broadening effect due to vibration. If the source is free from the thickness effect, the width of the Mössbauer spectrum is usually given with the natural line width, $\Gamma_{nat}$, as

$$\Gamma_{exp} = (2 + 0.270t_a)\Gamma_{nat} + \Delta\Gamma,$$

(1)

where $\Delta\Gamma$ is the systematic broadening and the thickness effect of the absorber is expressed by a factor $0.270t_a$. Here $t_a = n\sigma_0f$ with $n$ being the number of radioactive nucleus per unit area, $\sigma_0$ the maximal cross section for resonant nuclear absorption and $f$ the recoilless fraction of the absorber. For our absorber $CsCl$, we have $n = 1.075 \times 10^{21}cm^{-2}$, $\sigma_0 = 1.021 \times 10^{-19}cm^2$ and $f = 0.0145[9]$. The source $BaTiO_3$ might not be free from the thickness effect. For such a case, Eq.(1) should be converted into a form
\[
\Gamma_{\text{exp}} = \xi_s \Gamma_{\text{nat}} + (1 + 0.270 \tilde{t}_a) \Gamma_{\text{nat}} + \Delta \Gamma,
\]

where \(\xi_s = 1 + 0.270 \tilde{t}_a\) with \(\tilde{t}_a = \tilde{n} \sigma_0 \tilde{f}\). The value of \(\xi_s\) is not known at this moment, but it does not matter for the investigation of the effect of plates because the term depending on \(\xi_s\) disappears in the final expression. This fact can be seen later.

C. Measurement with plates

Let us now explore the case of the absorber placed between two parallel flat plates. We prepared the plates in the following manner. Silicon wafer plates of 3\(\times\)3\(\text{cm}^2\) with 0.58\(\text{mm}\) thickness were coated by gold with about 100\(\text{Å}\) thickness at room temperature using an evaporation method developed by the Surface Physics Group at Yonsei University. The roughness of the plate surface was on the order of 0.01\(\mu\text{m}\). The two plates were separated by 0.61\(\text{mm}\) with stainless stick spacers. Accuracy of parallelness was around 2\(\mu\text{m}\). The absorber, \(\text{CsCl}(90.0\text{mg})\), was formed in a very thin mylar square bag of 1\(\text{cm} \times 1\text{cm} \times 0.15\text{mm}\) at a volume density of 6\(\text{g/cm}^3\), equivalently 90\(\text{mg/cm}^2\) thickness which yields \(n \rightarrow n' = 1.613 \times 10^{21}\text{cm}^{-2}\) and was centered between the two plates to prevent it from touching the plate surfaces. Thermal effects were very small, i.e., the second-order Doppler shift was negligible, since the temperature variation during the experiment was \(\pm 0.2\text{K}\). In this experiment, we took such a geometry as the gamma-ray came along the direction perpendicular to the flat plates.

In this experiment, we obtained a very distinct and thin spectrum. The width of Lorentzian spectrum is \(\Gamma'_{\text{exp}} = 0.707 \pm 0.014\text{mm/s}\), equivalently \(\Gamma'_{\text{exp}} = (1.909 \pm 0.038) \times 10^{-7}\text{eV}\). In order to extract the effect of plates set around the absorber, let us rewrite Eq.(2) in the form

\[
\Gamma'_{\text{exp}} = \xi_s \Gamma_{\text{nat}} + (1 + 0.270 t'_a) \Gamma^{(a)} + \Delta \Gamma,
\]

where \(t'_a = n' \sigma_0 f = (1.613 \times 10^{21}\text{cm}^{-2}) \times (1.021 \times 10^{-19}\text{cm}^2) \times 0.0145 = 2.388\) and \(\Gamma^{(a)}\) is the natural line width modified by the plates. Subtracting Eq.(2) from Eq.(3), we find
\[ \Gamma^{(a)} = \frac{\Gamma'_{\text{exp}} - \Gamma_{\text{exp}} + (1 + 0.270t'_{a})\Gamma_{\text{nat}}}{1 + 0.270t'_{a}} \]  

(4)

The half-life of the first excited state \( \frac{5}{2}^+ \) in \(^{133}\text{Cs}\) is known to be \( \tau_{1/2} = 6.27 \pm 0.02 \text{ ns}[10] \), from which the natural line width, \( \Gamma_{\text{nat}} \), can be calculated as

\[ \Gamma_{\text{nat}} = \frac{\hbar}{\tau_{1/2} \ln 2} = (0.728 \pm 0.002) \times 10^{-7} \text{eV}. \]  

(5)

Substituting \( \Gamma'_{\text{exp}} = (1.909 \pm 0.038) \times 10^{-7} \text{eV}, \Gamma_{\text{exp}} = (2.149 \pm 0.038) \times 10^{-7} \text{eV} \) and \( \Gamma_{\text{nat}} = (0.728 \pm 0.002) \times 10^{-7} \text{eV} \) into Eq.(4), we obtain

\[ \Gamma^{(a)} = (0.487 \pm 0.010) \times 10^{-7} \text{eV}, \]  

(6)

from which the half-life modified by plates can be found as

\[ \tau_{1/2}^{(a)} = \frac{\hbar}{\Gamma^{(a)} \ln 2} = (9.37 \pm 0.19)\text{ns}. \]  

(7)

This value is larger than \( \tau_{1/2} = 6.27 \pm 0.02\text{ns} \) by 49.4%.

### III. DISCUSSION

Hence, our finding is that the life-time increases by 49.4% when the absorbing nucleus is placed between two parallel flat plates. The change of life-time, \( \Delta \tau = 3.10 \pm 0.19 \text{ ns} \), arises purely from the effect of plates, because all experimental conditions are the same except for setting plates around the absorber.

Why does the life-time become longer when a nucleus is placed between two parallel flat plates? It may be understood as a phenomenon caused by the self-interaction that photons (not necessarily real photons) emitted from the excited nuclei are reabsorbed by these nuclei after being reflected by plates.

Consider an excited nucleus put between two parallel flat plates. This excited nucleus emits virtual (even real) gamma-rays in arbitrary directions, and parts of them are reflected by plates. Since the plates are, of course, not perfect, some of the gamma rays are absorbed or pass through the plate. And the reflected gamma-rays may come back to be reabsorbed by
the nucleus. Through such a process, the population of the excited state in a nucleus could be amplified.

However, one may worry about that 81 KeV is too high energy for the gamma-ray to be reflected by the plates. Since the wavelength of 81 KeV gamma-ray is about 0.015 nm, the silicon plate would be almost transparent at such a short wavelength. Indeed, our Monte-Carlo simulation with the program GEANT3 shows that only 0.018 percent of the 81 KeV gamma-ray are reflected at the same energy. Nevertheless, if the process can be repeated many times, the effect must be enhanced.

Generally, the amount of nucleus decaying during $\Delta t$ is given by $\Delta N = -\lambda N \Delta t$, from which we obtain $N = N_0 \exp(-\lambda t)$, where $\lambda$ is the decay constant and $N_0$ is the initial value of $N$. If emitted photons can once return after being reflected by the plates, the equation is modified as $\Delta N = -\lambda N \Delta t + \sigma \lambda N \Delta t = -(1 - \sigma)\lambda N \Delta t$, where $\sigma$ is the reflection coefficient, i.e. $\sigma = 0.00018$ for the present case. If such a process is assumed to repeat $n$ times, we have

$$\Delta N = -(1 - \sigma)^n \lambda N \Delta t$$

(8)

For $\sigma = 0$, it reduces to $\Delta N = -\lambda N \Delta t$. Furthermore, $n = 0$ leads Eq.(8) to $\Delta N = -\lambda N \Delta$. This is the case without any plate, i.e. photons have no chance to return. Solving Eq.(8), we find

$$N = N_0 \exp(-\tilde{\lambda} t)$$

(9)

where $\tilde{\lambda} = (1 - \sigma)^n \lambda$, alternatively $h\tilde{\lambda} \equiv \tilde{\Gamma} = (1 - \sigma)^n \Gamma$. If $n = 2200$, we have $\Delta \Gamma / \Gamma = (\Gamma - \tilde{\Gamma}) / \Gamma = 0.33$, which implies $\Delta \tau / \tau_{1/2} = 0.492$. Let $t_0$ be the time when the photon consumes during its round trip between the nucleus and the plate, number of repeat of the process during the nuclear half-life is $n = \tau_{1/2} / t_0 = 1542$. Since the program GEANT3 is known to be efficient only for the gamma-ray energy larger than 100 KeV, the value of $\sigma$ may be flexible for 81 KeV gamma-ray. For instance, $\sigma = 0.00026$ renovates $n = 1540$ to retain $\Delta \Gamma / \Gamma = 0.33$. This analysis is anyway ad hoc.
IV. CONCLUSION

In this paper, we report our discovery that the decay of $^{133}$Cs in the first excited state was delayed when the nucleus was placed between two parallel flat plates. This phenomenon is based on the process that the population of the excited state of the nucleus is increased by reabsorption of the emitted photon into the same nucleus after being reflected by the plates.

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Table 1. Changes of Decay Constant

$^{99m}_{43}Tc$ Technetium internal conversion $\tau_{1/2} = 6.007h$, 2.2KeV E3 transition

### Chemical

- 1953 K. Bainbridge et al.
  \[ \frac{\lambda(KTcO_4) - \lambda(Tc_2S_7)}{\lambda(Tc_2S_7)} = (2.70 \pm 0.10) \times 10^{-3} \]

- 1980 H. Mazaki et al.
  \[ \frac{[\lambda(TcO_4) - \lambda(Tc_2S_7)]}{\lambda(Tc_2S_7)} = (3.18 \pm 0.7) \times 10^{-3} \]
  \[ \frac{[\lambda(TcS_7) - \lambda(Tc_2S_7)]}{\lambda(Tc_2S_7)} = (5.6 \pm 0.7) \times 10^{-4} \]

- 1999 A. Odahara, T. Tsutsumi, Y. Gono, Y. Isozumi, R. Katana, T. Kikegawa, T. Suda, T. Kajino
  \[ \frac{[\lambda(compound) - \lambda(metal)]}{\lambda(metal)} = \text{in progress} \]

### High pressure 10GPa

- 1952 K. Bainbridge et al.
  \[ [\lambda(10GPa) - \lambda(0Pa)]/\lambda(0Pa) = (2.3 \pm 0.5) \times 10^{-4} \]

- 1972 H. Mazaki et al.
  \[ [\lambda(10GPa) - \lambda(0Pa)]/\lambda(0Pa) = (4.6 \pm 2.3) \times 10^{-4} \]

### Low temperature

- 1958 D. Byers et al.
  \[ [\lambda(4.2K) - \lambda(293K)]/\lambda(293K) = (1.3 \pm 0.4) \times 10^{-4} \]

### External electric field gradient $\sim 2 \times 10^4 V/cm$

- 1970 H. Leunberger et al.
  \[ \frac{\Delta \lambda}{\lambda} \approx 10^{-4} \]

### Phase transition: ferroelectric $\rightarrow$ para electric

- 1972 M. Nishi et al.
  \[ \frac{\Delta \lambda}{\lambda} \approx (2.6 \pm 0.4) \times 10^{-3} \]