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Branching ratio for ^{10}C superallowed Fermi β decay

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The branching ratio for ^{10}C superallowed Fermi β decay has been measured accurately by a newly developed method. The result is $1.473\pm0.007\%$. The Ft value is derived as 3065.4 ± 14.7 sec, which is consistent with the Ft values determined accurately for heavier nuclei and with predictions of conserved vector current hypothesis. The method developed here can be applied to the high precision β-γ spectroscopy.

The vector coupling constant G_V derived from the ft value for the superallowed $0^+\rightarrow0^+$ decay is important for testing predictions of conserved vector current (CVC) hypothesis. It can also be used for the test of the three generation standard model when the hypothesis is established.[1-4]

Precise ft values of the superallowed $0^+\rightarrow0^+$ decays have been reported for eight nuclei.[5] A sharp difference of Ft values noted recently between the four lighter (^{14}O, ^{26}Al^m, ^{34}Cl, ^{38}K^m) and the four heavier (^{42}Sc, ^{46}V, ^{50}Mn, ^{54}Co) nuclei has been attributed to an incorrect evaluation of the $O(Z\alpha^2)$ correction to δ_R.[2] Here a corrected Ft is related to the measured ft as

$$Ft=ft(1+\delta_R)(1-\delta_C) \qquad (1)$$

where δ_R and δ_C stand for an outer radiative correction and a charge correction, respectively. In order to reduce Z dependent ambiguities of these corrections it is very valuable to measure ft values for very light nuclei.[2-4] It should be noted that δ_R calculated by Sirlin differs from that by Jaus and Rasche and the difference increases with Z.[2] In addition, δ_C is small for lower Z.[6,7]

This paper reports an accurate determination of the ft value for ^{10}C superallowed Fermi decay by developing a new method in obtaining the decay branch. ^{10}C has the lowest atomic number of nuclei, which decay by the $0^+\rightarrow0^+$ Fermi transition. Its study would give a critical datum to derive the G_V value and also give a proper interpretation for the finite difference of the ft value observed in the ^{14}O-^{26}Al pair.[2,3,8]

The ^{10}C decay is characterized by weak Fermi ($\sim1.5\%$) and strong Gamow-Teller ($\sim98.5\%$) decay branches.[9] As each decay is followed by the 1022 or 718 keV γ ray, the Fermi decay branch can be obtained by measuring relative intensities of these γ rays. So far the ft value of the Fermi decay was measured as 3112 ± 31 sec,[10] where the error was much larger than those of the above eight nuclei, and 96% of errors came from the uncertainty of the branching ratio. In this work three significant improvements were made to obtain the branching ratio accurately. They were the reduction of pile-up of pulses from intense 511 keV γ rays to the 1022 keV γ-ray peak, more precise measurement of the γ-ray relative efficiency, and higher statistics of γ-ray peak yields.

^{10}C was produced via the ^{10}B$(p,n)^{10}$C reaction using about 1 nA of 10 MeV pulsed beam from a cyclotron of the Institute for Nuclear Study, University of Tokyo. The beam was stopped at a Faraday cup 5 m down stream. A 10 mg/cm^2 enriched boron target (90% ^{10}B, 10% ^{11}B) was bombarded for 280 msec and the off-beam γ-ray single spectra were measured for a period of 260 msec beginning 10 msec after the end of bombardment. Five large Ge detectors, located at a distance of about 26 cm from the target in order to reduce pileup of pulses from coincident γ rays, were used. To suppress the 1022 keV sum peak yield N_p due to a random coincidence of the 511 keV γ rays, a 6.5 mm thick tungsten plate was placed in front of each detector. As the W plate attenuated the 511 and 1022 keV γ-ray intensities by 82% and 55%, respectively, the ratio of the N_p to the true 1022 keV peak yield N_t was much reduced to 7% of the value obtained without the W plate. Careful pileup rejection was also made using the ORTEC 572A amplifiers. The yield N_p was given by $N_p=2\tau N_a^2$, where 2τ and N_a stand for a resolving time and the 511 keV γ-ray yield, respectively. 2τ was measured at three different count rates of N_a, i.e., 1.2, 1.8, and 2.8 kcps by using a positron emitter of ^{11}C, produced by bombarding an enriched ^{11}B target (98.6%) with 10 MeV pulsed protons. A typical value of 2τ was obtained as 0.594 ± 0.006 μsec, independent of N_a as expected. In ^{10}C run N_a was constant at 0.8 kcps by keeping total count rate of about 25 kcps. The ratio of N_p to N_t was 6%–10%. Thus the effect of the sum peak was corrected with an uncertainty of 0.10%–0.18%, depending on the accuracy of 2τ. A typical spectrum observed in the ^{10}B$(p,n)^{10}$C reaction is shown in Fig. 1(a). The efficiency ratio of each Ge detector for 718 and 1022 keV γ rays was measured in the following way. It used the intensity balance of cascade γ transitions from isomeric

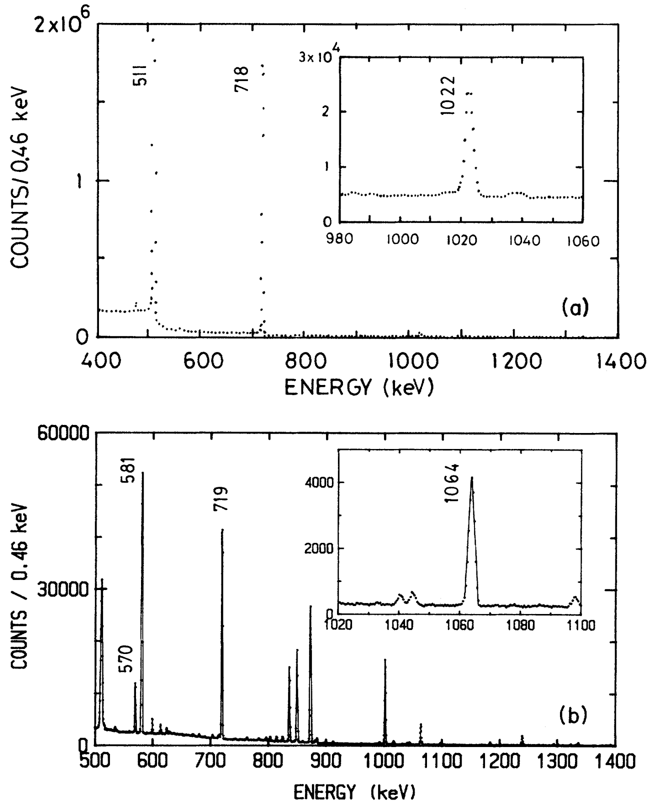

FIG. 1. (a) Off-beam γ-ray single spectrum from the $^{10}B(p,n)^{10}C$ reaction. (b) Off-beam γ-ray single spectrum from the $^{206}Pb(^{3}He,2p)^{207}Pb^{m}$ and $^{206}Pb(^{3}He,4n)^{205}Po^{m}$ reactions.

states of $^{207}Pb^{m}(t_{1/2}=810$ msec), which decays via 1064 and 570 keV γ rays, as well as of $^{205}Po^{m}(t_{1/2}=57$ msec), characterized by 581 and 719 keV γ transitions. Partial level schemes of $^{207}Pb^{m}$ and $^{205}Po^{m}$ are shown in Fig. 2. Note that they include γ transitions with energies similar to 718 and 1022 keV transitions of the ^{10}C decay. The assumption of the intensity balance of cascade γ transitions with energies E_i and E_j leads to the following equation:

$$\frac{Y(E_i)}{\varepsilon(E_i)}[1+\alpha(E_i)]=\frac{Y(E_j)}{\varepsilon(E_j)}[1+\alpha(E_j)]\,, \qquad (2)$$

where $\varepsilon(E_i)$, $\alpha(E_i)$, and $Y(E_i)$ indicate the γ-ray detection efficiency, total internal conversion coefficient, and γ-ray yield for the γ transition with energy E_i. Applying the equation for the cascade γ transitions in $^{207}Pb^{m}$ and $^{205}Po^{m}$ efficiency ratios, $\varepsilon(719)/\varepsilon(581)$ and $\varepsilon(1064)/\varepsilon(570)$ were obtained. Then two points of $\varepsilon(570)$ and $\varepsilon(581)$, with almost degenerate γ-ray energies, were fitted by using the efficiency curve obtained with a ^{152}Eu radioactive source.[11] Finally the efficiencies, $\varepsilon(718)$ and $\varepsilon(1022)$, were interpolated between these measured points by using an analytic expression.

$^{207}Pb^{m}$ and $^{205}Po^{m}$ isomers were populated by bombarding a 7.8 mg/cm^2 enriched ^{206}Pb target (99.7%) for 150 msec with about 2.5 nA of 38 MeV ^{3}He pulsed beam. The off-beam single spectra, measured for a period of 120

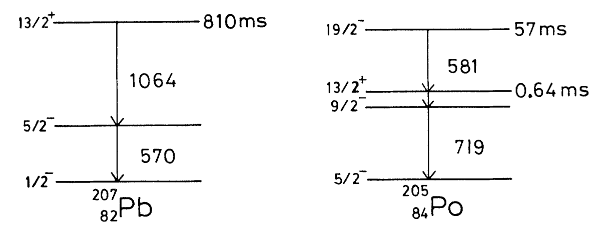

FIG. 2. Partial level schemes of $^{207}Pb^{m}$ and $^{205}Po^{m}$.

msec beginning 20 msec after the end of bombardment in the same experimental setup as those for the ^{10}C and ^{11}C cases, is shown in Fig. 1(b). The assignment of all discrete γ rays was made from comparison of γ spectra taken in the bombardment of three targets, enriched ^{206}Pb and ^{208}Pb and natural Pb, with 32, 32, and 38 MeV ^{3}He beams. Consequently the four γ-ray peaks of 570, 581, 719, and 1064 keV were confirmed to originate mainly from the isomers. Small impurities due to long-lived activities were corrected very accurately by measuring the γ rays of the produced radioactivities. Here it should be mentioned that γ-ray intensities were obtained by integrating counts above background. As each γ-ray peak was well separated from neighboring peaks the peak fit program was not used. Furthermore, angular distributions of these four γ-rays measured in the above off-beam period were shown to be isotropic.

The validity of the assumption mentioned in Eq. (2) was confirmed by the measurements of the γ-γ coincidence in the same off-beam period as in the case of the singles one and the decay curves for the 570, 1064, 581, and 719 keV γ rays. From the coincidence measurement the γ-ray intensities of the side feeding to the 570-keV state in ^{207}Pb and the 719-keV state in ^{205}Po, not through the isomers of $^{207}Pb^{m}$ and $^{205}Po^{m}$, were found to be less than 0.1% of the transition intensities from the isomers. These results are consistent with the systematics of isomers in the mass region of present interest.[12] The decay curves were measured by using three different pulsed beams of 20 μsec, 59 msec, and 0.5 sec, provided by the CYRIC cyclotron of Tohoku University. The results showed that three γ rays of 570 and 1064 keV and 581 keV followed the decay curves of $t_{1/2}=810$ msec and 57 msec, respectively and the 719 keV γ ray followed two decay curves of 0.64 and 57 msec as reported.[12] The effect of the short-lived isomer of 0.64 msec was shown to be negligible for the off-beam measurement beginning 20 msec after the end of the bombardment. As the electromagnetic properties of these four γ rays are well known to be of $E3$ (581 keV), $E2$ (719 keV), $E2$ (570 keV), and $M4$ (1064 keV) characters, total conversion coefficients α are calculated as $\alpha(581)=0.071$, $\alpha(719)=0.014$, $\alpha(570)=0.022$, and $\alpha(1064)=0.131$.[13] Here it should be noted that although calculated α values for low multipolarity agree quite well with experimental ones, α for high multipolarity is claimed to deviate a few percent from an experimental value.[14] Therefore we used the empirical α values of 0.069(1) and 0.126(3) for the 581 and 1064 keV transitions.

Finally the branching ratio for the ^{10}C Fermi decay was obtained individually for the five Ge detectors as 1.475(18)%, 1.481(19)%, 1.480(15)%, 1.468(14)%, and 1.467(14)%. A parenthesis indicates an error, where the error was obtained by quadratic addition of the statistical uncertainty of the 1022 keV γ-ray yield (0.51%–0.69%), the uncertainties of the γ-ray detection efficiency (0.74%–1.01%) and the pileup correction (0.10%–0.18%) and systematic error of the internal conversion coefficient for high multipolarity (0.3%). Here it should be noted that the decay branch to the 2.15 MeV state of ^{10}B was negligibly small.[15] Averaging these values we obtained an accurate branching ratio of 1.473(7)%, which is somewhat larger than that of Ref. 10, although they agree with each other within an experimental accuracy.

Recently new data were reported for the end-point energy of ^{10}C Fermi decay as 885.72(9) keV (Ref. 16) and for the half-life of ^{10}C as 19.290(12) sec.[17] With use of these data the ft value is obtained as 3011.5(144) sec. The statistical rate function f was evaluated by using the formula in Ref. 18. Then making an electron capture correction (0.31%),[19] an outer radiative correction (1.66%) (Ref. 2) and a charge correction (0.18%),[6] Ft is obtained as 3065.4(147) sec. The value agrees quite well with the Ft values of the accurately measured eight nuclei[2,4,7] and is consistent with the prediction of the CVC hypothesis.

Having established the CVC hypothesis, the Kobayashi-Maskawa mixing matrix element Vud is obtained from the relation. $G_v^2/G_\mu^2 = Vud^2(1+\Delta_\beta-\Delta_\mu)$ where G_v and G_μ stand for the effective nuclear vector coupling constant and effective muon coupling constant. The term, $\Delta_\beta-\Delta_\mu$ is the difference between the inner radiative corrections to nuclear β decay and muon decay. It has been evaluated as $\Delta_\beta-\Delta_\mu=2.37(18)\%$.[2] The values for G_v, defined as

$$G_v = \frac{1}{2Ft}\frac{2\pi^3\hbar^7\ln 2}{m^5c^4},$$

and G_μ are obtained from the present ^{10}C experiment and from the muon lifetime as $G_v = 1.1509(28)\times10^{-5}(\hbar c)^3$ GeV^{-2} and $G_\mu = 1.166\,387(10)\times10^{-5}(\hbar c)^3$ GeV^{-2}, respectively. Thus we obtain Vud [$Vud=0.9752(24)$]. With use of the values for the matrix elements, Vus 0.2197(19) and $Vub=0.0046(46)$,[20] the unitarity was tested as $Vud^2+Vus^2+Vub^2=0.9993(48)$, which is consistent with three generation unitarity. At this moment the uncertainty is still dominated by the branching ratio. However, as it could be reduced by using the present method, it might be valuable to study further on charge and radiative corrections.

In conclusion the new method was developed to obtain the accurate branching ratio for the very weak Fermi decay of ^{10}C. We have determined the most accurate ft value. The result supports the CVC hypothesis and unitarity of the three generation standard model.

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