Superallowed Fermi beta transition of ^{62}Ga

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A superallowed Fermi β transition ($J^\pi = 0^+$, $T = 1$) from ^{62}Ga ($A = 4n + 2$) has been identified. The measured half-life and β ray end point energy are $T_{1/2} = 116.4 \pm 1.5$ msec and $E_{\beta max} = 8.3 \pm 0.3$ MeV, respectively. The Ft value for the transition has been evaluated with the measured half-life and estimated β ray end point energy from a phenomenological analysis of the Coulomb displacement energies of isobaric analog states. The obtained value is $Ft = ft(1 + \delta_R)(1 - \delta_C) = 3103 \pm 44$ sec which turns out to be 0.6% larger than that expected for such $0^+ - 0^+$ superallowed β transitions.

[RADIOACTIVITY ^{62}Ga [from $^{64}Zn(p,3n)$]; measured $T_{1/2}$ $E_{\beta max}$; deduced ΔE_C, $\mathcal{F}t$ value.]

I. INTRODUCTION

It has been known that the precise determination of the $\mathcal{F}t^*$ values for superallowed Fermi β transitions between $J^\pi = 0^+$, $T = 1$ analog states[1-6] provides not only a direct test of the conserved vector current theory which predicts exact equality of these $\mathcal{F}t$ values, but also our best measure of the vector coupling constant for nuclear β decay. In this sense, there has been a considerable amount of work up to ^{54}Co in connection with more precise redetermination of the β ray end point energy and half-life for each transition as well as with more detailed reevaluation of the theoretical uncertainty due to electromagnetic radiative and nuclear charge-dependent corrections.

Using appropriate charge-dependent corrections[2] and evaluating radiative effects up to order $Z^2\alpha^3$, Hardy *et al.*[4] showed that the resulting 16 $\mathcal{F}t$ values for $0^+ - 0^+$ superallowed β transitions were constant within two parts in 3000 ($\mathcal{F}t = 3081.7 \pm 1.9$ sec). Similar analyses using slightly different charge-dependent corrections were made by Raman *et al.*[5] for a total of eighteen $0^+ - 0^+$ superallowed β transitions which gave a resulting value of $\mathcal{F}t = 3088.6 \pm 2.1$ sec. In general, the charge-dependent corrections are due to the imperfect overlap between the initial and final states as well as to the charge-dependent configuration mixing. That is, the corrections are model dependent, and thus, some uncertainty arises depending on how these effects are evaluated. In such a situation, it might be better to leave these corrections out altogether and to see a trend of f^Rt values with Z (f^R differs from f by the outer radiative corrections of order α, $Z\alpha^2$, and $Z^2\alpha^3$), with the intention of obtaining the f^Rt value at $Z=0$ for the derivation of the desired vector coupling constant. This f^Rt analysis by Wilkinson[6] for eight $0^+ - 0^+$ superallowed β transitions with recently redetermined high precision experimental data[7] has shown that the experimental f^Rt values were sufficiently represented by the expression

$$f^Rt = (f^Rt)_{Z=0} + aZ^{1.86} \qquad (1)$$

with fitting values of

$$(f^Rt)_{Z=0} = (3084.3 \pm 3.0) \text{ sec}, \quad a = (4.5 \pm 1.0) \times 10^{-2} \text{ sec}. \qquad (2)$$

From this point of view, it should be worthwhile to look for heavier $0^+ - 0^+$ superallowed Fermi β transitions above ^{54}Co in $A = 4n + 2$ nuclei. The 0^+, $T = 1$ analog state of ^{58}C turned out to be 203.2 keV above the 1^+, $T = 0$ ground state,[8] and hence no $0^+ - 0^+$ superallowed β transition could be expected in the decay of ^{58}Cu. Then the next possible candidates, although the nature of the ground states is quite uncertain, are ^{62}Ga, ^{66}As, and ^{70}Br which could be produced by the $^{64}Zn(p,3n)$ ^{62}Ga, $^{70}Ge(p,5n)$ ^{66}As, and $^{74}Se(p,5n)$ ^{70}Br reactions, respectively.

A high energy β activity with a half-life of approximately 120 msec found on a zinc target bombarded with 44-MeV protons was preliminarily reported.[9-10] This activity was considered to be due to the superallowed beta transition of ^{62}Ga; however, the precise measurement was disturbed by the intense background. The present work is intended to identify the radioactive nuclide ^{62}Ga and to measure the intensity of the expected $0^+ - 0^+$ superallowed Fermi β transition. The uncertainty in the estimation of

β ray end point energy from a phenomenological analysis of the Coulomb displacement energies of IAS is also discussed.

II. EXPERIMENTAL PROCEDURES

The nuclide ^{62}Ga was produced through a ^{64}Zn-$(p,3n)$ ^{62}Ga reaction with protons of energies from 36 to 52 MeV from the synchrocyclotron of the Institute for Nuclear Study, University of Tokyo. A set of carbon absorber foils was used to lower the energy of the 52-MeV protons from the accelerator. Beam chopping was achieved by a mechanically rotating shutter with a pulsed beam interval of 2 sec. A target chamber with a 50-μm thick titanium window was located in the next room at about 15 m from the beam chopper. The targets used were 0.5-mm thick zinc plates (^{64}Zn natural abundance is 48.9%). The incuded high energy β activities on the zinc target were measured with a plastic scintillator mounted on a 56AVP photomultiplier. With the help of a crystal oscillator controlled timing device, the amplified signals were recorded into a 4096-channel pulse height analyzer operated in the eight-subdivided mode and a 400-channel multiscaler of 4-msec channel stepping. Since the detector system was slightly affected by the intense beam burst, the beam intensity was kept at a reasonable level during the measurement, and the obtained decay curve was analyzed after 40 msec from the termination of the beam burst.

In order to reduce the background disturbance, the following efforts were made: (i) After the beam chopping device, a pair of quadrupole magnets was used to focus the beam right onto the target. (ii) Proton beam passing through the target was brought to a distance from the target chamber for the same reason. (iii) Carefully estimated heavy shields for neutrons and γ rays were arranged surrounding the beam tube and β ray detector. (iv) The ion source of the synchrocyclotron was turned off during the data taking periods. This could reduce the background level by a factor of about 2. (v) Bombarded targets were replaced every 40 sec (after 20 beam bursts) by an automatic target changer with a loading capacity of 500 targets in order to avoid the high energy piling up activities such as ^{64}Ga ($E_{\beta\,max}$ = 6.1 MeV, $T_{1/2}$ = 2.6 min) and ^{63}Ga ($E_{\beta\,max}$ = 4.5 MeV, $T_{1/2}$ = 33 sec). This could give us another factor of 5 for the background reduction.

The energy calibration of the detector system was made with end point energies of 7.545 ± 0.003 MeV,[11] 6.032 ± 0.002 MeV,[11] and 3.788 ± 0.002 MeV[11] for the positron decays of 3.20-sec ^{58}Cu, 0.426-sec ^{46}V, and 4.91-sec ^{27}Si which were produced by the (p,n) reactions on ^{58}Ni, ^{46}Ti, and ^{27}Al, respectively. In the high energy portion of the obtained spectra, there was a 20-msec component due to the decay of ^{12}B ($E_{\beta\,max}$ = 13.4 MeV) produced by the ^{12}C(n,p) ^{12}B reaction in the plastic scintillator. Therefore, several scintillators of different diameters and thickness were tested, and consequently, scintillators of 28 and 40 mm in thickness were used for measuring the half-life and β ray end point energy of ^{62}Ga by evaluating the S/N ratio of ^{62}Ga to ^{12}B.

III. EXPERIMENTAL RESULTS

A. End point energy measurement

Bombarding with 44-MeV protons (see Fig. 3 for the excitation function), β ray energy spectra were recorded sequentially into the eight-subdivided 4096-channel pulse height analyzer with a 200-msec switching period. Figure 1 shows the result of a Kurie plot analysis for the high energy portion of the obtained spectra. In order to avoid the disturbance of 20-msec ^{12}B activity as mentioned above, the spectra, measured from 220 to 420 msec after the beam burst, were taken for the analysis. The spectra obtained from 1220 to 1420 msec were subtracted as the background. Taking into account the energy loss of β particles in the target and titanium window, the end point energy for the ^{62}Ga superallowed β transition was obtained to be $E_{\beta\,max}$ = 8.3 ± 0.3 MeV by an averaging of four independent measurements.

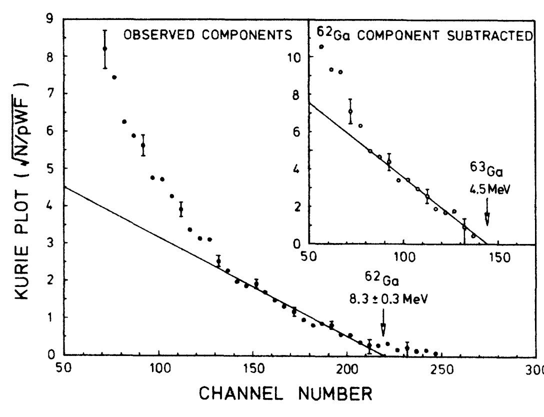

FIG. 1. Kurie plots of the β ray energy spectrum from a 0.5-mm thick zinc target bombarded by 44-MeV protons measured from 220 to 420 msec after the beam burst. The spectrum measured from 1220 to 1420 msec after the beam burst has already been subtracted as background. The closed circles show the Kurie plot of the ^{62}Ga component which gives the end point energy of $E_{\beta\,max}$ = 8.3 ± 0.3 MeV. The open circles (in the inset) show the Kurie plot of the ^{63}Ga component after subtracting the ^{62}Ga contribution which gives the end point energy of $E_{\beta\,max}$ = 4.5 MeV. All data points are from summations of 5 successive channels.

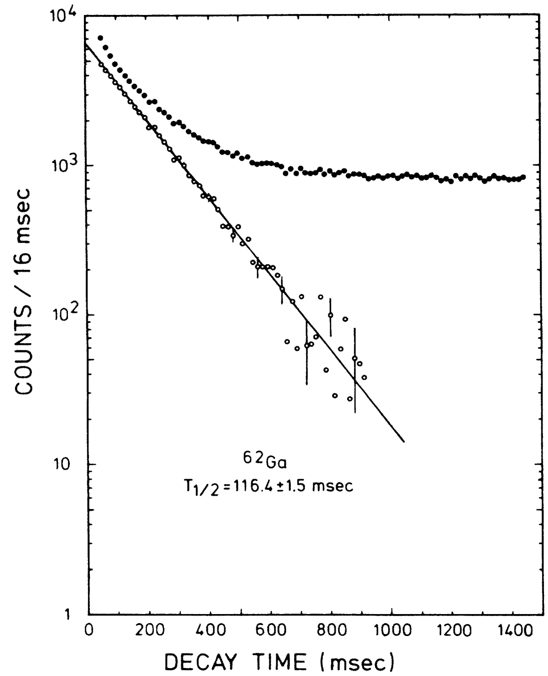

FIG. 2. Decay curve of ^{62}Ga obtained by the least squares fitting analysis considering a 20-msec (^{12}B), an unknown (^{62}Ga), and a constant (long lived background activity) component. The closed circles show the observed data for measuring β rays of energies higher than 5 MeV. The obtained half-life of ^{62}Ga is $T_{1/2} = 116.4 \pm 1.5$ msec (open circles). All data points are from summations of 4 successive channels (16 msec).

B. Half-life measurement

For the measurement of the ^{62}Ga half-life, the signal pulses were discriminated at 5 MeV and were recorded into the 400-channel multiscaler of 4-msec channel width. The obtained data points were analyzed with a least squares fitting program by taking into account the following three components: a 20-msec ^{12}B, an unknown ^{62}Ga, and a constant long lived background activity. The resulting decay curve is shown in Fig. 2, and a value of $T_{1/2} = 116.4 \pm 1.5$ msec was obtained for the half-life of ^{62}Ga.

C. Confirmation measurement

In order to confirm that this 8.3-MeV 116-msec β activity is due to the decay of ^{62}Ga, approximately 50 mg of 95% enriched ^{64}Zn oxide deposited on a thin Mylar film was bombarded with 44-MeV protons. Besides ^{62}Ga β activity, only an 11-msec ^{12}N component produced by the ^{12}C(p,n) ^{12}N reaction was observed. A thin copper plate was also bombarded for the background confirmation and the 116-msec component was not observed in this case.

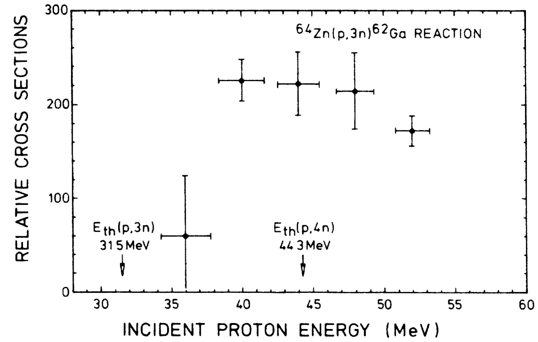

FIG. 3. Measured excitation function for the ^{64}Zn$(p,3n)^{62}$Ga reaction versus incident proton energies with evaluated experimental uncertainties. The estimated threshold energies for the $(p,3n)$ and $(p,4n)$ reactions are indicated by arrows.

A crude excitation function for the ^{64}Zn$(p,3n)$ ^{62}Ga reaction was measured with protons of energies from 32 to 52 MeV. The result is shown in Fig. 3 with evaluated experimental uncertainties. The behavior of the excitation function of this 8.3-MeV 116-msec activity seems to support the idea that this activity could be produced by the $(p,3n)$ reaction on ^{64}Zn. On the other hand, there is no other possible reaction product giving such a high energy and short lived β activity through the bombardment of ^{64}Zn by 44-MeV protons. Moreover, if the state of ^{62}Ga in question were not a 0^+, $T=1$ IAS, the half-life of ^{62}Ga would be at least a few seconds or longer. From all this evidence, this 8.3-MeV 116-msec β ray is considered to be due to the superallowed Fermi β transition of ^{62}Ga.

IV. COULOMB DISPLACEMENT ENERGIES

For the purpose of precise determination of the $\mathcal{F}t$ value for the observed β transition, the present measurement of β ray end point energy, however, contributes less because of a large experimental error. Moreover, an estimation of the β ray end point energy from the Q values of reactions such as ^{58}Ni(^{10}B,^{6}He) ^{62}Ga, ^{54}Fe(^{14}N,^{6}He)^{62}Ga, and ^{58}Ni(^{12}C,^{8}Li)^{62}Ga is practically not available. Thus in the present work, the systematic trend of the Coulomb displacement energies for neighboring isotopes was reexamined, and the end point energy of the observed β transition was estimated from the following phenomenological analysis with reasonable accuracy.

In general, the Coulomb displacement energy ΔE_C is expressed in the form[12]

$$\Delta E_C = \frac{6e^2}{5R}(Z + \tfrac{1}{2})(1 - \epsilon), \tag{3}$$

where ϵ refers to a correction factor depending on

Z. For a fixed isotope pair, this form can be simplified as

$$\Delta E_C = \mu_Z A^{-1/3} \quad (4)$$

by using a charge-dependent parameter μ_Z. Then, in order to see the mass number dependence of the Coulomb displacement energies in such a simple expression, the experimental value of ΔE_C (Refs. 12–17) was plotted as a function of A in the logarithmic scales as shown in Fig. 4. Generally, the gradient for each isotope pair does not correspond exactly to $A^{-1/3}$ and seems to indicate a slight dependence on A. Therefore, the $A^{-1/3}$ term should also have some Z-dependent correction for each isotope line. A simple phenomenological expression for this could be written as

$$\Delta E_C = \mu_Z A^{-1/3\lambda_Z} \quad (5)$$

by introducing another Z-dependent parameter λ_Z. These parameters μ_Z and λ_Z could then be determined by fitting the experimental values for each line. Applying this expression to five experimental values of ΔE_C for Ni-Cu even mass isotopes ($T=1$ to 5),[12,13,15] the root mean square fitting uncertainty turned out to be 5.8 keV with values of μ_Z and λ_Z as 31.991 MeV and 0.89319, respectively. In the case of four known experimental values of ΔE_C for Zn-Ga even mass isotopes ($T=2$ to 5),[13,14] the rms deviation was 14.0 keV with $\mu_Z = 27.678$ MeV and $\lambda_Z = 0.74291$. Table I summarizes the results of this analysis, which gives us an estimated value of the Coulomb displacement energy of ^{62}Zn-^{62}Ga ($T=1$) to be $\Delta E_C = 9960 \pm 10$ keV (and thus the β ray end point energy to be $E_{\beta\,\max} = 8156 \pm 10$ keV). A functional fitting for the same even mass experimental data by the empirical form of Long *et al.*[18] also predicts the same results of $\Delta E_C = 9960 \pm 10$ keV with the rms deviations of 5.8 and 14.3 keV for Ni-Cu and Zn-Ga isotope pairs.

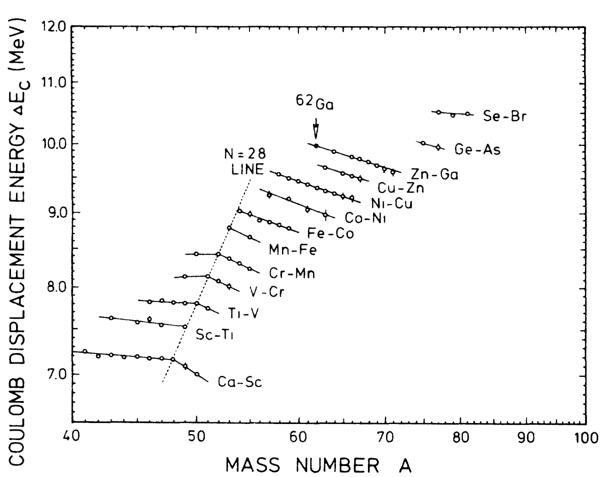

FIG. 4. Experimental values of the Coulomb displacement energies ΔE_C (Refs. 12–17) plotted as a function of mass number A in logarithmic scales. The closed circle indicated by an arrow shows the estimated value of $\Delta E_C = 9960 \pm 10$ keV for the ^{62}Zn – ^{62}Ga ($T=1$) case.

TABLE I. Phenomenological fitting of the Coulomb displacement energies for Ni-Cu and Zn-Ga isotope pairs. The experimental values are given in the third column with their references in the fourth column. The estimated values are given in the last column with fitting uncertainties in parentheses. The fitting uncertainty for the present case ($A=62$, $T=1$) was assumed to be 10 keV by taking into account the rms value of 9.4 keV for the other fitting uncertainties.

Ni-Cu ($\mu_Z = 31.991$ MeV, $\lambda_Z = 0.89319$)				
A	T	Exp. ΔE_C (keV)	Ref.	Calc. ΔE_C (keV)
58	1	9552 ± 6	15	9550 (−2)
60	2	9454 ± 6	13	9454 (0)
62	3	9360 ± 6	13	9362 (+2)
64	4	9271 ± 6	13	9274 (+3)
66	5	9212 ± 15	12	9190 (−22)

Zn-Ga ($\mu_Z = 27.678$ MeV, $\lambda_Z = 0.74291$)				
A	T	Exp. ΔE_C (keV)	Ref.	Calc. ΔE_C (keV)
62	1	present case		9960 (10)
64	2	9879 ± 6	13	9882 (+3)
66	3	9813 ± 6	13	9807 (−6)
68	4	9733 ± 6	13	9735 (+2)
70	5	9620 ± 50	14	9665 (+45)

V. $\mathcal{F}t$ VALUE

It was not our intention to go into a detailed discussion of the $\mathcal{F}t$ value. However, the $\mathcal{F}t$ value for the ^{62}Ga decay was evaluated just to see how close this new point comes to the precisely investigated values of the other $0^+ - 0^+$ superallowed β transitions.

The f value, taking into account the effects of finite nuclear charge distribution, electron screening, energy-dependent outer radiative correction of order α, and finite mass of nucleus, was obtained from the parametrized expression[19] to be $f = (2.654 \pm 15) \times 10^4$ using the estimated β ray end point energy in the previous section and the nuclear radius parameter of $r_0 = 1.264$ fm.[13] The

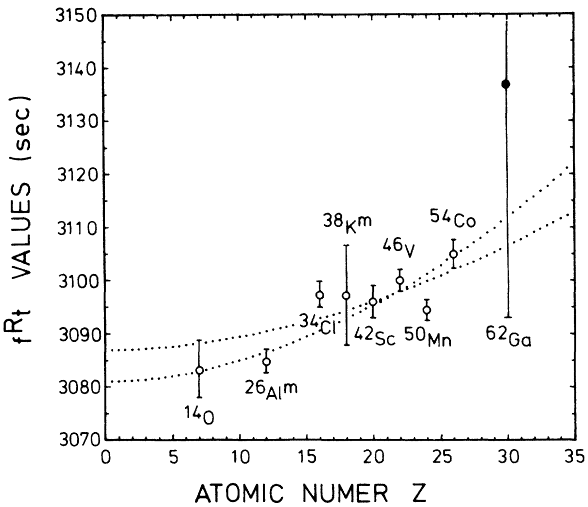

FIG. 5. f^Rt values for the superallowed Fermi β transition plotted as a function of atomic number Z of the daughter nucleus. The data are fitted to the form of $f^Rt=(f^Rt)_{Z=0}+aZ^{1.86}$ as discussed in Ref. 6. The area between the two dotted lines covers the fits at the plus-and-minus one standard deviation levels. The result of the present work is shown by a closed circle with the evaluated uncertainty.

error quoted here is an associated error with the uncertainty of β ray end point energy. The observed half-life $T_{1/2}=116.4\pm1.5$ msec was corrected for the electron capture decay of 0.129% (Ref. 20) to be $T_{1/2\beta^+}=116.6\pm1.5$ msec. Also, weak positron decay branchings to some excited states of ^{62}Zn could be quite possible due to such a high decay energy; however, in the present evaluation, they have not been considered to maintain a certain consistency with the other analyses. Then the ft value turns out to be $ft=3093\pm44$ sec.

The higher order radiative corrections of order $Z\alpha^2$ and $Z^2\alpha^3$ were estimated to be $\delta_{R2}=1.080\%$ and $\delta_{R3}=0.324\%$ with the expressions of Jaus.[21] This gives us the value of $f^Rt=ft(1+\delta_{R2}+\delta_{R3})=3137\pm44$ sec. Strictly speaking, this way of correcting the higher order radiative effects in the present case may not be quite right; however, the difference should be much smaller than the present experimental uncertainty. The correction due to imperfect overlap between the initial and final states was calculated by Raman *et al.*[5] to be 1.09% for the case of ^{62}Ga. Although the correction for charge-dependent configuration mixing is not exactly known for the ^{62}Ga case, it could be smaller than a few tenths of a percent, and thus, has to be ignored. Then the $\mathfrak{F}t$ value for the ^{62}Ga superallowed β transition turns out to be $\mathfrak{F}t=f^Rt(1-\delta_C)=3103\pm44$ sec.

This $\mathfrak{F}t$ value agrees with the recent value of $\mathfrak{F}t=3084.9\pm2.0$ sec which was obtained by adjusting the resulting values of Refs. 4 – 6 within the uncertainty discussed previously, and the value could be even a few tenths of a percent smaller if the charge-dependent isospin mixing were taken into account. This fact could be more positive evidence supporting the assignment of the observed 8.3-MeV 116.4-msec β ray to the decay of ^{62}Ga. In order to avoid the uncertainty due to the isospin mixing correction, the obtained f^Rt value for ^{62}Ga transition is also plotted in Fig. 1 of Ref. 6 and is shown in Fig. 5. In spite of a relatively large experimental uncertainty, it seems to fit a trend of f^Rt values versus Z showing a noticeable charge-dependence, and thus to support the present work.

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