Excited 0^+ states and electric monopole transitions in ^{118}Sn

H. Kawakami, N. Yoshikawa, K. Komura,* M. Koike, and H. Yamada†
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan
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Electric monopole transitions of 1758.04 (0_1^+-0_g^+), 2056.64 (0_2^+-0_g^+), and 298.58 keV (0_2^+-0_1^+) in ^{118}Sn were observed in the internal conversion electron spectra with a $\pi\sqrt{2}$ iron-free magnetic β-ray spectrometer. Anisotropies of γ-γ angular correlations were measured for the 0-2-0 spin sequence to confirm the excited 0^+ states. The dimensionless ratio of $E0$ to $E2$ transition probabilities $X=B(E0,0^+-0_g^+)/B(E2,0^+-2_1^+)$ for the first, second, and third excited 0^+ states were deduced as 0.0081 ± 0.0008, 0.13 ± 0.02, and <0.035, respectively. The relative monopole strength from the second excited 0^+ state at 2056.6 keV was obtained as $\rho(0_2^+$-$0_1^+)/\rho(0_2^+$-$0_g^+) = 7.3\pm0.8$.

[RADIOACTIVITY ^{118}Sb(3.5 min) from ^{121}Sb$(p,4n)^{118}$Te -^{118}Sb; measured I_{ce}, I_γ, γ-$\gamma(\theta)$, ^{118}Sn observed 0^+ levels, deduced branching ratio $X(E0/E2)$, relative monopole strength $\rho(E0)$. Natural target.]

I. INTRODUCTION

The low-lying excited 0^+ states and the monopole transitions are important in the study of nuclear structure. However, only a few data for the $E0$ transitions in the spherical nuclei have been reported because of the difficulties of experimental conditions.

The $E0$ transitions associated with nuclear structure in ^{100,102}Ru, ^{106}Pd, and ^{112,114}Cd have been discussed in the works by the group of Koike,[1,2] Ohya,[3] and Julin,[4] respectively. In this paper we investigate the electric monopole transitions in the closed proton shell nucleus ^{118}Sn.

Three excited 0^+ states at 1758, 2056, and 2496 keV have been reported through the (p,p'), (p,t), (t,p), (p,d), and (d,p) reactions,[5–12] as well as radioactivity experiments.[13–16] Hattula *et al.*[15] have extensively investigated the low-lying states with γ-γ coincidence and angular correlation measurements with Ge(Li)-NaI detectors. Ikegami and Udagawa[16] have reported three $E0$ transitions of 1.76, 2.06, and 2.08 MeV in ^{118}Sn, but no quantitative discussion has been given. Bäcklin *et al.*[17] have published their results about $E0$ transition from the 1757.8 and 2056.5 keV 0^+ states by in-beam spectroscopy.

There are also many theoretical works[18–24] about low-lying level schemes of even tin isotopes with the microscopic calculation based on the quasiparticle Tamm-Dancoff or quasiparticle second Tamm-Dancoff approximation. No theoretical prediction for the electric monople strength, however, has been published in the framework of these microscopic theories so far.

In this paper we present the data on $E0$ transitions from the first three excited 0^+ states in ^{118}Sn through the precise measurements of the conversion electron spectrum.

II. EXPERIMENTAL PROCEDURE

A natural antimony target 1.0 g/cm^2 thick was bombarded for 40 h by a proton beam of 0.3 μA from the synchrocyclotron at the Institute for Nuclear Study (INS), University of Tokyo. The radioactive isotope of ^{118}Te was chemically separated from the target material by an ion-exchange method after dissolution in aqua regia. The carrier-free tellulium activities were spontaneously deposited over an area of 2×20 mm^2 into a copper foil of 10 μm thick for the electron source. The internal conversion electrons were measured with the INS $\pi\sqrt{2}$ iron-free magnetic β-ray spectrometer with $\rho=75$ cm. The overall momentum resolution was 0,1%. The momentum analyzed electrons were counted with a 2 mm thick Si(Li) detector. Details of the counting system were already described in Ref. 1.

Two γ-ray sources were prepared for singles spectrum measurements. One was the same as the electron source (source I) containing ^{119}Te activities, and the other was the ^{118}Sb ($T_{1/2} = 3.5$ m) (source II) extracted from source I by a milking procedure. The γ-ray spectra were observed with a 40 cm^3 Ge (Li) detector. The energy resolution was 2.5 keV (FWHM) at 1332 keV.

In order to confirm the excited 0^+ states, the γ-γ angular correlation measurements were made for the (0^+-2_1^+-0_g^+) sequence with two Ge (Li) detectors and source I. The γ-ray source 1.5×5 mm was mounted in an acrylic resin container. The distances between the source and detectors were 6.0 and 7.0 cm. The angular correlation was measured at two angles of 90° and 180 °, because the anisotropies show the distinguishable value for the 0-2-0 spin sequence in comparison with other spin sequences.

The observed spectra of the γ-rays and conversion electrons were analyzed by an automatic peak search program (KEI-10) (Ref. 25) with the TOSBAC-3400 computer at INS.

III. RESULTS

The conversion electron spectra of the $E0$ transitions are shown in Fig. 1. Transition energies and the origin of the electrons are indicated in parentheses. The energies and relative intensities of electrons and γ rays are listed in Table I. The 294.11 keV electron peak is supposed to be the 298.6 keV L conversion or 323.3 keV K conversion in ^{118}Sn, or the 324.58 keV K conversion in ^{119}Sb. However, there are no γ-ray peaks around these energy regions, as is shown in Fig. 2, which is the partial γ-ray spectra observed with the same source I as

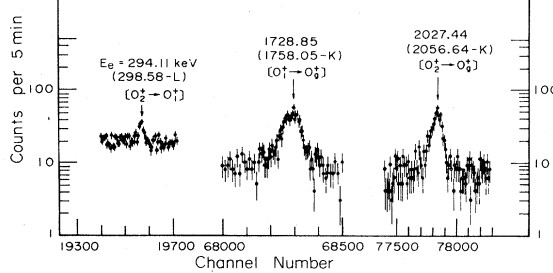

FIG. 1. Spectra of internal conversion electrons of electric monopole transitions in ^{118}Sn.

for electron measurement. Furthermore, considering the internal conversion coefficient and energy sum relations, we conclude that the 294.11 keV electron peak is associated with the 298.58 keV $E0$ (0_2^+-0_1^+) transition in ^{118}Sn. The corresponding K line was not resolved from the strong 271 keV L line in ^{119}Sb.

Positive evidence of the γ-ray peak was not found around the 1728.85 and 2027.44 keV $E0$ transitions, as is illustrated in Fig. 2. We, therefore, assigned the 1728.85 and 2027.44 keV conversion electron lines as $E0$ transitions. The experimental upper limit of the γ-ray intensities are given in Table I. The $E0$ transitions from the third excited 0^+ state at 2496.56 keV to the other 0^+ states could not be identified.

Pair-electron decay corrections for the $E0$ transition were made with the calculated values by Wilkinson.[26] The intensity ratios of pair decay to single electron emission were estimated to be 0.20 and 0.52 for the 1758.05 and 2056.64 keV transitions, respectively.

Relative electron intensities reported by Ikegami and Udagawa[16] were not quite consistent with the present results. The electron energies and intensities are the following: 0.52-K (60 ± 10), 0.84-K(8 ± 2), 1.74-K(9 ± 2), 2.06-K(7 ± 2), and 2.08-K(6 ± 2) MeV, where the intensities are shown in parentheses. Their results deviate about 20–80% from the present values. The present relative γ-ray intensities were in good agreement with those of Hattula *et al.*[15] For the calculation of the experimental conversion coefficients, the 1229.3 keV pure $E2$ transition (2_1^+-0_g^+) was used for the normalization between the electron and γ-ray intensities with the table by Hager and Seltzer.[27] Experimental conversion coefficients are in good agreement with theoretical values.

From the coincidence spectra gated with the 1229.3 keV (2_1^+-0_g^+) γ-ray, we obtained the anisotropies of the γ-γ angular correlation, as is given in Table II. The quoted error for the theoretical value is due to the uncertainty of the finite solid angle correction[28] of the Ge(Li) detectors. The present experimental values are in good agreement within an error with the theoretical prediction for the spin sequence 0-2-0.

The decay scheme in ^{118}Sn based on the present experiment is shown in Fig. 3. Ratios of the transition intensities are given in parentheses. The line widths are nearly proportional to the intensities. The intensities of $E0$ transitions are shown in open lines with the width multiplied by factor of 500.

TABLE I. Energies and relative intensities of internal conversion electrons and γ rays.

Electron energies (keV)	Shell	Transition energies (keV)	Spin-parity sequence	I_e	Intensities I_γ Present	Ref. 15	Conversion coefficients[a] Exp.	Theo.
294.11±0.04	L	298.58±0.04	$0_2^+ \to 0_1^+$	42± 9	≤ 2.6		≥1.2 (−2)	$E0$
								$M1$: 3.2 (−3)
								$E2$: 4.6 (−3)
	K	323.3			≤ 0.33		≥ 9.1 (−2)	$M1$: 2.2 (−2)[c]
	(Sb)	324.6[b]						$E2$: 2.4 (−2)[c]
499.53±0.03	K	528.73±0.03	$0_1^+ \to 2_1^+$	152±12	19.1±0.9	15.5 ±0.2	5.7±0.5(−3)	$E2$: 5.42(−3)
798.14±0.07	K	827.34±0.07	$0_2^+ \to 2_1^+$	37± 5	16 ±1	14.4 ±1.0	1.7±0.3(−3)	$E2$: 1.72(−3)
		1098.5 ±0.5	$\to 2_1^+$		3.2±0.9	1.8 ±0.3		
1200.13±0.03	K	1229.33±0.03	$2_1^+ \to 0_g^+$	100	100	100	7.17(−4)	$E2$: 7.17(−4)
1238.03±0.05	K	1267.23±0.05	$0_3^+ \to 2_1^+$	17± 6	20.7±0.8	23.2 ±1.0	5.9±2.3(−4)	$E2$: 6.74(−4)
		1699.7 ±0.1	$\to 2_1^+$		3.1±0.5	2.3 ±0.2		
1728.85±0.05	K	1758.05±0.05	$0_1^+ \to 0_g^+$	34± 2	≤ 1.7		≥1.4 (−2)	$E0$
								$M1$: 4.2 (−4)
								$E2$: 3.7 (−4)
		1907.2 ±0.2	$\to 2^+$		1.8±0.4	1.6 ±0.2		
2027.44±0.05	K	2056.64±0.05	$0_2^+ \to 0_g^+$	41± 4	≤0.35		≥8.4 (−2)	$E0$
								$M1$: 3.0 (−4)
								$E2$: 2.8 (−4)
		2327 ±0.8	$(2^+) \to 0_g^+$		0.43±0.09	0.5 ±0.2		
2467.36	K	2496.56	$0_3^+ \to 0_g^+$	<2.3				($E0$)

[a]Notation of conversion coefficient $m(-n)$ means $m \times 10^{-n}$.
[b]If this peak is the K line in Sb isotope, the transition energy is 324.6 keV.
[c]These values are mean values of Sn and Sb isotopes.

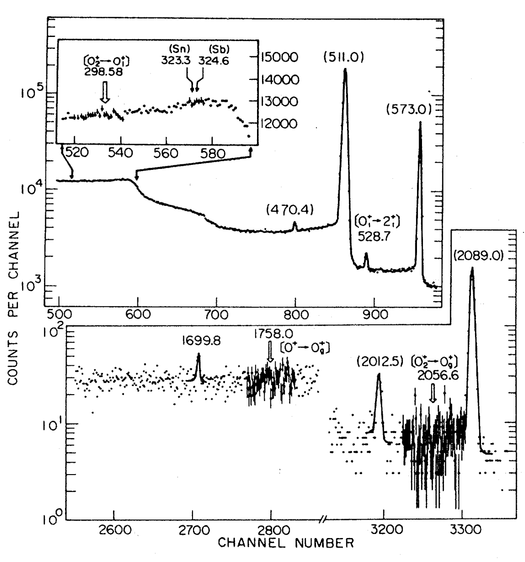

FIG. 2. Single γ-ray spectra obtained with source I. The energies of the γ rays from mainly the decay of ^{119}Te ($T_{1/2}=4.7$ d), are indicated in parentheses. Open arrows show the corresponding positions of γ rays for the $E0$ transitions observed in the present measurement.

Using branching ratios from the excited 0^+ states we deduced the dimensionless ratio of $E0$ to $E2$ transition probabilities X, from the following equation[29]:

$$X=\frac{B(E0,0^+-0_g^+)}{B(E2,0^+-2_1^+)}$$

$$=2.53\times 10^9 A^{4/3}\frac{I_{eK}(E0)}{I_{eK}(E2)}$$

$$\times\frac{E_\gamma{}^5(E2)\times\alpha_K(E2)}{\Omega_K}\ ,$$

TABLE II. The anisotropies of the γ-γ angular correlation measurements for the 0^+-2_1^+-0_g^+ sequence.

E_γ (keV)	$E(0^+)$ (keV)	$W(180°)/W(90°)$ Experiment	Theory[a]
528.73	1758.06	1.68±0.16	
827.34	2056.64	1.82±0.25	1.89±0.07
1267.23	2496.56	1.71±0.24	

[a]Corrected for the finite solid angle of two Ge(Li) detectors. The quoted error is due to the correction.

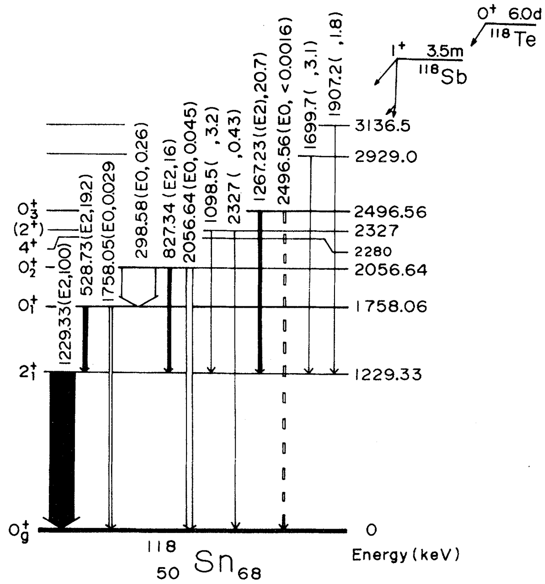

FIG. 3. The decay scheme of ^{118}Te (0^+, $T_{1/2}=6.0$ d) and ^{118}Sb (1^+, $T_{1/2}=3.5$ m). Branching ratios of transitions are given in parentheses. The line width is nearly proportional to the intensities except for $E0$ transitions. The $E0$ transition intensities are shown in open lines and the width are multiplied by 500. The 2496 keV $E0$ transition, which was not definitely detected in the present experiment, is shown with the dashed open line.

where $I_{eK}(E\lambda)$ is K-electron intensity in the $E\lambda$ transition, and $E_\gamma(E2)$ indicates the $E2$ transition energy in MeV. The electronic factor Ω_K is a known function of an atomic number Z and transition energy E. The numerical values of Ω_K were obtained with the table by Hager and Seltzer.[30] The experimental dimensionless ratios deduced for the 1758.06, 2056.64, and 2496.56 keV 0^+ states are given in Table III. The present ratios, $X = 0.0081 \pm 0.0008$ and 0.13 ± 0.02 for the first and the second excited 0^+ states, are in fairly good agreement with the results by Bäcklin *et al.*[17]

The branching ratio of the monopole strength from the 2056.64 keV state was deduced as

$$\frac{\rho(E0,0_2^+-0_1^+)}{\rho(E0,0_2^+-0_g^+)}=7.3\pm0.8$$

from the relative electron intensity

$$\frac{I_{eL}(E0,0_2^+-0_1^+)}{I_{eL}(E0,0_2^+-0_g^+)}=1.02 \ .$$

The theoretical K/L ratio used for the 298.58 keV (0_2^+-0_1^+) transition was estimated to be 7.7 from Ref. 30.

TABLE III. Experimental and theoretical values for the dimensionless ratio X and relative monopole strength ρ.

	Experiment	Theory[b]
$X(0_1)$	0.0081 ± 0.0008[a]	
$X(0_2)$	0.13 ± 0.02	0.013 (for $X = \beta^2$)
$X(0_3)$	<0.035	
$\dfrac{\rho(0_2^+-0_1^+)}{\rho(0_2^+-0_g^+)}$	7.3 ± 0.8	

IV. DISCUSSION

Theoretical dimensionless ratio X of $E0$ to $E2$ transition probabilities from the excited 0^+ state is estimated on the basis of the quadrupole phonon model.[31]

The nuclear surface and Hamiltonian are given as

$$R=R_0\Big[1+\sum_\mu \alpha_\mu Y_{2\mu}^*\Big] ,$$

$$H=\tfrac{1}{2} B\sum_\mu |\dot{\alpha}_\mu|^2+\tfrac{1}{2} C\sum_\mu |\alpha_\mu|^2 ,$$

where B and C are the mass and stiffness parameters, and α_μ five quadrupole variables.

The reduced $E2$ transition probability is written as

$$B(E2,0_g^+-2_1^+)=\left[\frac{3}{4\pi}ZeR_0^2\right]^2\times\frac{5}{2}\frac{\hbar}{\sqrt{BC}} ,$$

and the monopole stength from the two-phonon 0^+ to the ground 0^+ states is expressed by

$$\begin{aligned}\rho&=[0^+|\mathfrak{M}(E0)|0_g^+]\\&=\frac{3Z}{4\pi}\frac{\sqrt{5}}{2}\frac{\hbar}{\sqrt{BC}}\\&=\frac{\sqrt{2}}{5}\frac{4\pi}{3}\frac{B(E2,0_g^+-2_1^+)}{Ze^2R_0^4} .\end{aligned}$$

Then, the branching ratio X is obtained as

$$\begin{aligned}X\left[\frac{B(E0,0^+-0_g^+)}{B(E2,0^+-2_1^+)}\right]&=\frac{5}{2}\frac{\rho^2e^2R_0^4}{B(E2,0_g^+-2_1^+)}\\&=\left[\frac{4\pi}{3ZeR_0^2}\right]^2\\&\quad\times B(E2,0_g^+-2_1^+) .\end{aligned}$$

The reduced transition probability $B(E2)$ is also written[32] with the nuclear deformability β as

$$B(E2,0_g^+\text{-}2_1^+)=\left[\frac{3}{4\pi}ZeR_0{}^2\right]^2\beta^2 .$$

The dimensionless ratio in this model, then, is written as $X=\beta^2$. Using the experimental value of β = 0.116 from Coulomb excitation,[32] we can estimate the value X = 0.013. The experimental value for the first excited 0^+ states, $X(1758)$ = 0.0081, is about $\frac{2}{3}$ of the theoretical value, and the second 0^+ state, $X(2056)$ = 0.13, is as great as a factor of 10, as is compared in Table III. The value for the third excited 0^+ state at 2496 keV, $X(2496) < 0.035$, is consistent with the phonon model prediction X = 0.013.

According to the experimental lifetime of the first excited 0^+ state by Bäcklin *et al.*,[33] a ratio of the reduced transition probabilities is calculated as

$$\frac{B(E2,0_1^+-2_1^+)}{B(E2,2_1^+-0_g^+)}=1.39\pm0.27 .$$

The phonon model prediction of 2 is not consistent with this value, nor experimental values in the Pd and Ru region,[34] about 0.5, which is used for estimation of the monopole strength in ^{102}Ru by Koike *et al.*[2]

For the first excited 0^+ state, Bron *et al.*[35] have reported that the 0_1^+ state is the deformed band head on the basis of in-beam γ-ray spectroscopy. They have proposed the rotational-like band up to 12^+ states for $^{112-118}$Sn. On the assumption of this rotational band, the very small value, $X(1758)$ = 0.0081, is qualitatively consistent with the shape difference between the ground (spherical) and the first excited 0^+ states (deformed).

The large value $\rho(0_2^+\text{-}0_1^+)/\rho(0_2^+\text{-}0_g^+) = 7.3\pm0.8$ suggests the second excited 0^+ state has the character similar to the first excited 0^+ state rather than the ground state. Very recently Wenes *et al.*[36] reported theoretical results on doubly-even Sn nuclei. They consider low-lying states as the mixture of vibration and rotational band.

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*Present address: Low Level Radiation Laboratory, Faculty of Science, Kanazawa University, Tatsunokushi, Ishikawa-ken 939-12, Japan.
†Present address: Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830.

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