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Study on Nuclear Shakeoff

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〈Abstract〉

The probability of K-shell electron shakeoff in nuclear β^+ decay of ^{65}Zn has been determined from measurements of Cu Kx-0.511-0.511 triple coincidence spectrum for the study of nuclear shakeoff. The coincidence measurements of the Cu K x-ray with 1.116 Mev gamma ray of ^{65}Cu were used to determine the x-ray absorption and detector efficiency factors. The nuclear shakeoff probability in β^+ decay of Zn was found to be $(26.68\pm7.50)\times10^{-4}$, which was larger than in the earlier work, and also was considerably larger than the LS theory with the factor of 4 to 5. It was suggested at this time that more experimental work as well as additional theoretical work would be needed to try to explain the nuclear shakeoff.

원자핵 Shakeoff 연구

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물 리 학 과
(1986. 9.30 접수)

〈요 약〉

Cu Kx-0.511-0.511의 3중 동시계수 스펙트럼 측정으로 ^{65}Zn의 β^+ 붕괴에 따른 K-궤도전자 shakeoff probability를 결정하여 nuclear shakeoff 현상을 연구하였다. Cu Kx과 1.116 Mev 감마선과의 동시계수 스펙트럼을 측정하여 x-선 흡수와 계측기 효율인자를 결정하였다. ^{65}Zn의 β^+ 붕괴에 따른 핵 shakeoff probability에 대하여 $(26.68\pm7.50)\times10^{-4}$의 값을 얻었으며 이 값은 지난번 측정된 실험값보다 크며 LS 이론과는 4내지 5배 큰 값이 되었다. 앞으로 nuclear shakeoff 현상의 보다 정확한 설명을 위하여서는 더 많은 실험 및 이론적 연구가 있어야 할 것으로 생각된다.

I. Introduction

Nuclear shakeoff, which is one of autoionization processes, has been the subject of extensive theoretical and experimental study in recent years.[1,2,3] Autoionization has been theorized as coming from three mechanisms. The first, called "shakeoff" and being the predominant one, is the removal of an orbital electron due to the sudden change of Coulomb charge during nuclear $\beta^\pm$ decay. This sudden change in charge can also initiate a second mechanism, called "shakeup", which is the excitation of an atomic electron to another bound state. There is also the possibility of a third mechanism, called "direct collision", which is the Coulomb interaction of an emerging $\beta^\pm$ particle with an orbital electron. The probability for "shakeup" is believed to be small except at very low Z values. "Direct collision" seems to play a role only if the β^+ particle kinetic energy is of the same order of magnitude as the binding energy of an atomic electron.

Various approaches for explaining the processes of nuclear shakeoff associated with nuclear $\beta^\pm$ decay both on theoretical and experimental sides have been taken. Until recently, the theoretical predictions for the probability of K-shell electron ejection by nuclear shakeoff accompanying β^- decay, $P_k(\beta^-)$, were approximately a factor of 2 smaller than the experimentally determined probabilities[4,5]. Recent theoretical work by Law and Suzuki(LS),[6] however, appears to have restored agreement between the theoretical and experimental values. This agreement was accomplished when LS introduced into the earlier theories of Law and Campbell (Refs 7 and 8) and of Isozumi, Shimizu, and Mukoyama (ISM) (Refs 5 and 9) Dirac-Fock-Slater wave functions which described the initial and final states more exactly. This recent theory of LS, however, does not resolve the discrepancy which exists between theory and experiment for K-shell electron shakeoff in β^+ decay, $P_k(\beta^+)$. In contrast to β^-decay, where a large number of isotopes have been studied, only five experimental studies of K-shell electron shakeoff in β^+ decay have been reported, two on ^{64}Cu(Refs 10 and 11), one on ^{58}Co(Ref. 12), and one on ^{65}Z nR(ef. 13). In all cases the value of $P_k(\beta^+)$ determined by these experiments is approximately a factor of 2 larger than that predicted by the recent LS theory. LS suggest the difference may be due to the final wave function for β^+ decay which may be more complicated than previously believed, or the initial and final state screening factors which may be different for nuclear β^- decay or electron capture. The lack of experimental values for $P_k(\beta^+)$, compared to the large number of studies in the K-shell electron shakeoff in β^- decay $P_k(\beta^-)$, is due principally to the strong electron capture branches which exist in most nuclear β^+ decay isotopes. It is our aim in this study to obtain more precise experimental information on the K-shell electron shakeoff in nuclear β^+ decay, which would may allow a more detailed comparison with existing experiments and theory. Led by the earlier work[12,13] this experiment used a Si(Li) spectrometer for x-rays, a much more complete coincidence analeysis system, and the improved desingned electronic circuitry and experimental arrangement. ^{65}Zn was chosen again for this study because of its relatively simple decay scheme and long half life.

Ⅱ. Experimental Procedures

1. ^{65}Zn source

The ^{65}Zn source made at the University of Missouri Reactor with its initial activity of 0.328 μCi was used for this work. The source was prepared from ^{65}Zn activity produced by the neutron irradiation of 10mg of ^{65}Zn for 24.25h at $4.6\times10^4 n/cm^2$ sec and had decayed for approximately three half-lives. For source, drops of active solution were evaporated onto 0.07mm thick Mylan backings. After drying, the source was covered with a second piece of Mylar and sandwiched between two 1mm thick polyethylene absorbers. This combination was then placed in contact with the Be window of the Si(Li) detector to provide maximum efficiency for this detector.

Fig. 1 shows the decay scheme of ^{65}Zn. ^{65}Zn has strong(98.5%) electron capture(EC) branches and weak(1.5%) β^+ branch. In determing $P_k(\beta^+)$ with such an isotope, the K x-rays produced by shakeoff in β^+ decay must be differentiated from those produced in

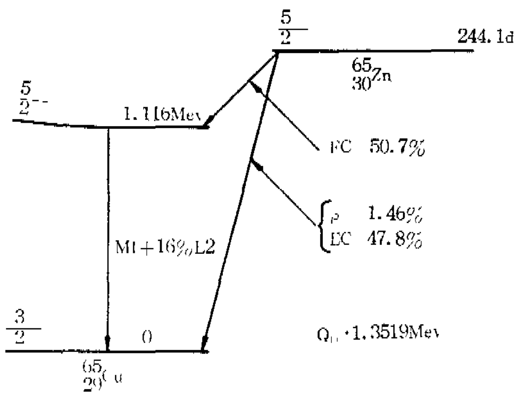

Fig. 1. Decay scheme of ^{65}Zn

EC. This can be done by requiring their coincidence with the positron or with annihilation radiation, as was done in this experiment. Although the weak(1.5%) β^+ branch of ^{65}Zn magnified these difficulties and led to rather large experimental uncertainties, the relatively long half life, and the fact that the product of x-ray absorption and detection efficiency factors could be determined by coincidence measurements between the 1.116Mev gamma ray and the Cu K x-rays produced in EC, made a worthwhile experiment possible.

2. Detectors

An ORTEC 7,000 series Si(Li) x-ray detector with 4mm diameter, 4.2mm sensitive depth, 0.008mm Be window, 10mm window-to-detector distance, and resolution width(FWHM) of 160 eV at 5.9keV, was used in these measurements. The Si(Li) detector used an ORTEC 739A amplifier set at 6 usec shaping to drive the MCA input and an ORTEC 551 SCA windowing between 6.5 and 11.8keV to drive the stop on the ORTEC 457 TAC. The annihilation photons were detected with a 7.6cm diameter ×7.6cm long NaI(Tl) detector and a 12.7cm diameter×15.2cm long NaI(Tl) detector. The SCA windows selected the 0.511Mev photopeak and their crossover timing outputs were fed into a fast coincidence circuit whose resolving time was set at to 50 nsec.

3. Electronic circuitry

Fig. 2 schematically shows the configuration of detectors and electronic circuitry used in this study. Because $P_k(\beta^+)$ can be determined by the detection of Cu K x-rays in coincidence with the two 0.511Mev gamma rays produced in the β^+ annihilation, two NaI (Tl) detectors collinear with the sample were used to detect the annihilation gamma rays subsequent to β^+ decay and the Si(Li) detector was used to detect the Cu K x-rays emitted as a result of the K-shell electron shakeoff. The main feature of the electronic circuitry is the time-to-amplitude converter(TAC) which gives a pulse height distribution for the time spread between the start and stop pulses arising from the NaI(Tl) and Si(Li) detectors, respectively. The emphasis of the electronic circuitry was given on recording accidental and true-plus-accidental coincidence concurrently in the same experiment by use of both the "accidental" and "prompt" single channel analyzers (A-and P-SCA) on the output from TAC. These routed P and A pulses to different memory halves of the MCA recording the K x-ray spectra.

Ⅲ. Data Analysis

1. K-shell electron shakeoff probability in β^+ decay, $P_k(\beta^+)$.

The probability for K-shell electron ionization in the nuclear β^+ decay, $P_k(\beta^+)$, can be calculated from the number of K x-rays(Kx) in coincidence with the two 0.511Mev positron annihilation gamma rays. The total number of the Kx-0.511-0.511 coincidence due to the K-shell electron shakeoff, N(Kx-0.511-0.511), is given by

$$N(\text{Kx-}0.511\text{-}0.511) = N_0 f_{\beta^+} \Omega_1 E_1(0.511) E_2(0.511)\ E_f(\text{coin})\ P_k(\beta^+)\ \omega_k(\text{Cu})\ a(\text{CuKx})\ E_k(\text{CuKx}), \quad (1)$$

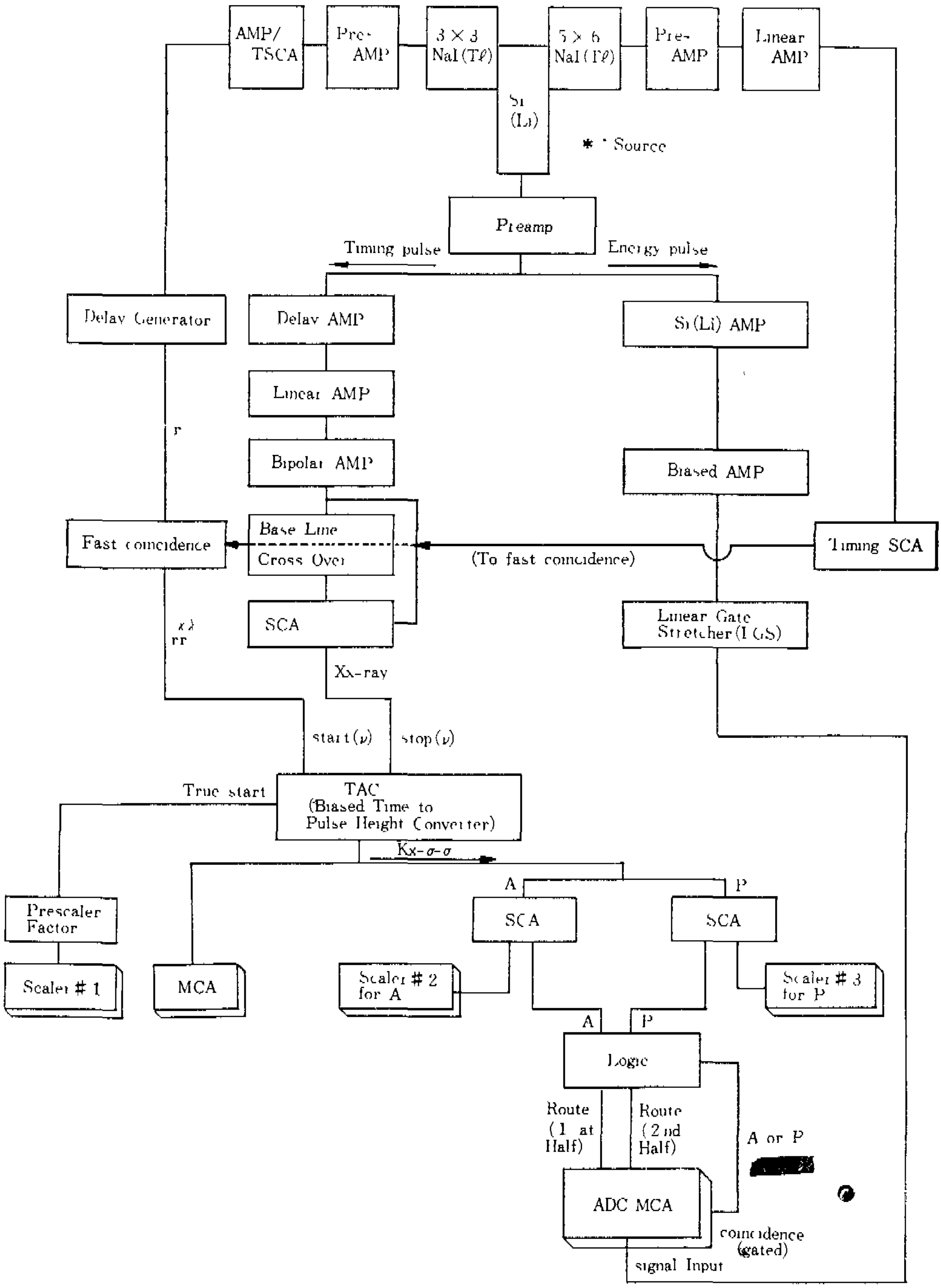

Fig. 2. Schematic diagram of detectors and circuits

where N_0 is the ^{65}Zn decay rate, f_{β^+} is the fraction of ^{65}Zn decaying via β^+ emission, ω_k(Cu) is the Cu K-shell fluorescence yield, a(CuKx) is the attenuation factor due to absorption, E_k(CuKx) is the total K x-ray detector efficiency, E_f(coin) is the fast coincidence efficiency, and $E_1(0.511)$ and Ω_1 are the intrinsic photopeak efficiency and solid angle subtended for the 7.6cm×7.6cm NaI(Tl) detector, and $E_2(0.511)$ is the intrinsic photopeak efficiency for the 12.7cm×15.2cm NaI(Tl) detector.

The numbers of coincidence of two 0.511Mev positron annihilation radiation, N(0.511-0.511), are related with N_0. f_{β^+}, Ω_1, E_1, E_2, and E_f, such as

$$N(0.511\text{-}0.511) = N_0 f_{\beta^+} \Omega_1 E_1(0.511)\ E_2(0.511)\ E_f(\text{coin}) \quad (2)$$

Thus, using the the 0.511-0.511 coincidence rate and rearranging Eq.(1), the K-shell electron shakeoff probability in β^+ decay of ^{65}Zn is given as follows

$$P_k(\beta^+) = \frac{N(\text{Kx-}0.511\text{-}0.511)}{N(0.511\text{-}0.511)} \cdot \frac{1}{\omega_k(\text{Cu})a(\text{CuKx})E_k(\text{CuKx})} \quad (3)$$

2. X-ray absorption and detector efficiency factor

The x-ray absorption and detector efficiency factors, ω_k(Cu) a(CuKx) E_k(CuKx), can be determined by auxiliary coincidence measurements of the Cu K x-rays with the 1.116Mev gamma rays in the 50.7% electron capture branch fo the ^{65}Zn decay. With the ^{65}Zn source in exactly the same position as for the Cu K x-ray-0.511Mev -0.511Mev runs, the SCA on the 12.7cm×15.2cm NaI(Tl) detector was adjusted to window on the the 1.116Mev photopeak. The total number of 1.116Mev gamma rays recorded with the NaI(Tl) detector, $N(1.116)$, is given by

$$N(1.116)\quad N_0 f_{EC} \Omega_2 E_2(1.116), \quad (4)$$

where f_{EC} is the fraction of ^{65}Zn decaying via electron captures to the 1.116Mev level of ^{65}Zn and Ω_2 is the solid angle subtended by the 12.7cm×15.2cm NaI(Tl) detector. The total number of the coincidences of Cu Kx-rays with the 1.116Mev gamma rays, N(Kx-1.116), is also given by

$$N(\text{Kx-}1.116)\quad N_0\, f_{EC}\, \frac{K}{T}\ \omega_k(\text{Cu})\ a(\text{CuKx})\ E_k(\text{CuKx}) \cdot \Omega_2 E_2(1.116), \quad (5)$$

where $K/T = 0.90$ is the K-shell-to-total ratio for electron capture to the 1.116Mev level.

Substitution of Eq.(4) into Eq.(5) gives the x-ray absorption and detection efficiency factors, ω_k(Cu)a(CuKx)E_k(CuKx), as follows:

$$\omega_k(\text{Cu})\ a(\text{CuKx})\ E_k(\text{CuKx}) = \frac{N(\text{Kx-}1.116)}{N(1.116)} \cdot \frac{T}{K} \quad (6)$$

Ⅳ. Results

1. TAC spectrum

The simultaneous recording of accidental and true-plus-accidental coincidences by use of both the "accidental" and "prompt" single channel analyzers on the output from the time-to-amplitude converter(TAC) were measured. These single channel analyzers routed P and A pulses to different halves of the multichannel analyzer(MCA) memory recording the K x-ray spectra.

Fig. 3 shows a TAC spectrum of Kx-0.511-0.511 coincidence for a typical trial and A-SCA window settings.

These window widths were varied from 70 to 200 nsec for different runs. Since subtraction of accidental coincidences requires that the relative window widths be accurately known, periodic checks on both the P-SCA and A-SCA width were made during the course of the experiment.

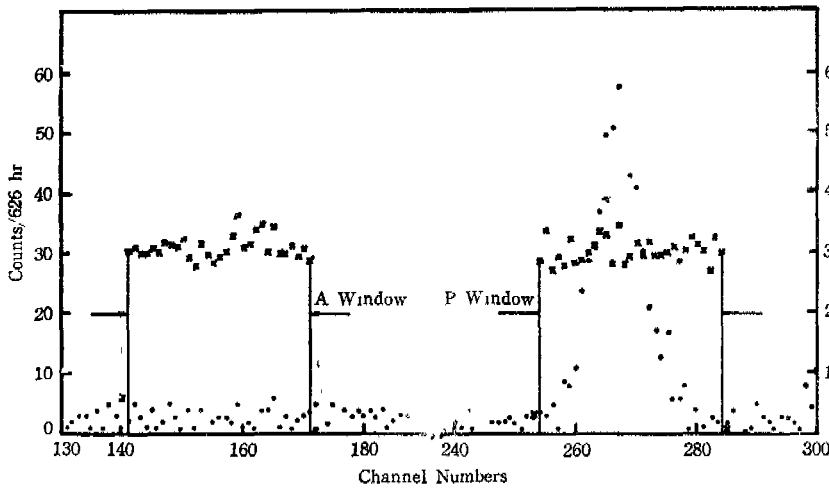

Fig. 3. TAC coincidence spectrum, and A-SCA and P-SCA window settings

2. K x-ray single spectrum

Single K x-ray spectrum from the 0.33 μCi ^{65}Zn source are shown in Fig. 4.

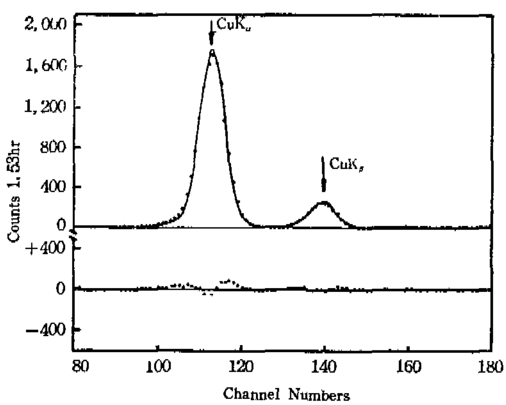

Fig. 4. K x-ray single spectrum emitted from ^{65}Cu

Two x-ray peaks appearing on the spectrum are K_α and K_β rays emitted from ^{65}Cu. The solid line on the spectrum is the computer fitted components and differences between the experimental data and fitted spectrun are plotted near the bottom of graph. These K_α and K_β x-rays emitted from ^{65}Cu were measured in coincidence with the 1.116Mev gamma rays of ^{65}Cu as well as the two 0.511Mev positron (β^+) annihilation radiations for the study of the nuclear shakeoff of ^{65}Zn in β^+ decay.

3. Kx-1.116 coincidence spectrum

Since ^{65}Zn decays either to the ground state of ^{65}Cu in the 47.8% electron capture and 1.46% positron emission or to the 1.116Mev excited state of ^{65}Cu in the 50.7% electron capture branch of the ^{65}Zn decay, the K x-rays emitted from ^{65}Cu can be coincided with the 1.116Mev gamma rays of ^{65}Cu.

Fig. 5 shows the Kx-ray-1.116Mev gamma ray coincidence spectrum. where Cu K_α and Cu K_β x-ray also appeared.

The upper figure shows the prompt coincidence spectrum(with the fitted components) and the lower figure shows the accidental coincidence spectrum. As seen in Fig. 5, the number of Kx-1.116 accidental coincidences are found to be rather less compared to the prompt coincidence counts. The difference between the counts of the prompt and accidental coincidences gives the true coincidences of Kx-1.116 coincidence run.

The total number of the Kx-1.116 coinciden-

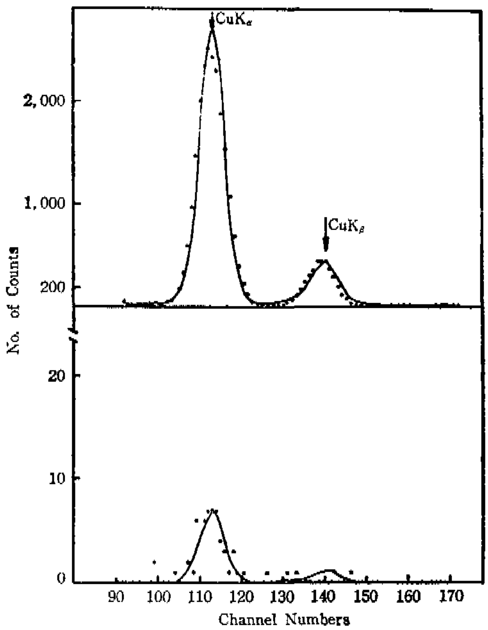

Fig. 5. Cu Kx-1.116 coincidence spectrum. The graph shows the prompt(P) and accidental(A) coincidence spectra with the least squared computer fitted components.

ces, N(Kx-1.116), were first determined from least squared computer fits both to the prompt and accidental spectrum in a program which used the Cu and Zn Kx-ray spectra and a linear continum as the input library. And than the true coincidence counts of Kx-1.116 coincidence run were determined from the difference between the counts of the prompt and the accidental coincidences. The number of 1.116MeV gamma rays, N(1.116), were counted on the TAC true starts scaler.

Table I shows the data obtained for N(Kx-1.116) and N(1.116), and the calculated x-ray absorption and detector efficiency factors. The x-ray absorption and detector efficiency factors were calculated by Eq. (6), using the data of N(Kx-1.116) and N(1.116), and also the value of K/T=0.90.

Table I. Data obtained for N(Kx-1.116) and N(1.116), and the calculated ω_k(Cu) a(CuKx) E_k(CuKx)

Run Number	N(Kx-1.116) (No/hr)	N(1.116) (No/hr)	ω_k(Cu) a(CuKx) E_k(CuKx)
1	0.2623×10^4	1.4567×10^6	0.2001×10^{-2}
2	0.2452×10^4	1.4302×10^6	0.1905×10^{-2}
Average			0.1953×10^{-2}

4. Kx-0.511-0.511 coincidence spectrum

Fig. 6 shows the measured the CuKx-0.511-0.511 prompt(P) and accidental(A) coincidence spectrum with the least squared computer fitted components. The Cu K$_\alpha$ and Cu K$_\beta$ x-rays emitted from ^{65}Cu, coincided with the two 0.511Mev annihilation photons, are appeared both in the prompt and the accidental

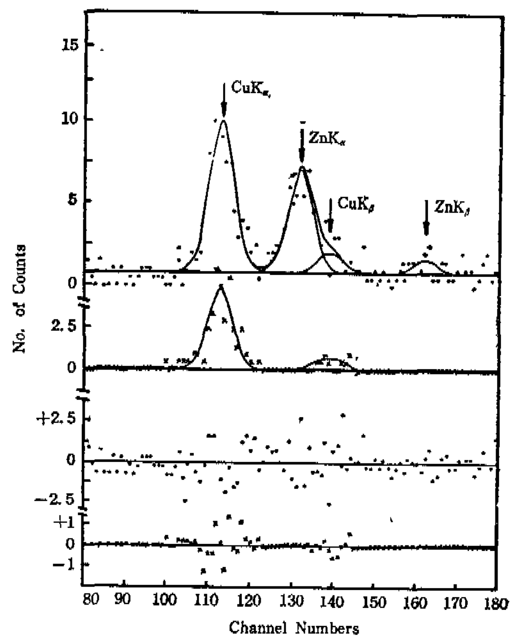

Fig. 6. Kx 0.511-0.511 coincidence spectrum. The prompt(P) and accidental(A) coincidence spectrum with the computer fitted components are shown. The figure also shows the difference spectrum between the experimental and fitted spectrum.

coincidence spectrum, while the Zn Kx-rays due to Zn fluorescence are seen only in the prompt coincidence spectrum. Also shown in Fig. 6 is the difference spectrum between the experimental and the computer fitted spectrum. The number of coincidence counts between the 0.511Mev positron annihilation gamma rays subsequent to β^+ decay, N(0.511-0.511), was counted on the TAC true starts scaler.

Table Ⅱ shows the data of N(Kx-0.511-0.511) and N(0.511-0.511). N_P and N_A represent the total number of prompt and accidental Cu K x-ray coincidences, respectively, recorded during a run. N represents the difference between N_P and N_A and is the net

Table Ⅱ. Data obtained for N(Kx-0.511-0.511) and N(0.511-0.511)

Run number	Live Time (h)	$N(Kx$-0.511-0.511)			N(0.511-0.511)
		N_P	N_A	N	
1	329	95.07	40.97	54.03	9.692×10^6
2	165	44.31	21.84	22.47	4.635×10^6

number of true Cu Kx-ray-0.511Mev-0.511 Mev coincidences. Those number of N(Kx-0.511-0.511) and N(0.511-0.511) were used to calculate the K-shell electron shakeoff probability in β^+ decay, $P^s(\beta^+)$.

5. Shakeoff probability, $P_k(\beta^+)$

The shakeoff probability for K-shell electron ionization in the nuclear β^+ decay, $P_k(\beta^+)$, of ^{65}Zn can be calculated by Eq. (3) using the data obtained in the Cu Kx-ray-0.511Mev-0.511Mev coincidence and Cu Kx-ray-1.116Mev coincidence shown in Table Ⅰ and Table Ⅱ For two different runs of Cu Kx-0.511-0.511 coincidence for $P_k(\beta^+)$ calculation, the average value of the x-ray absorption and detector efficiency factors, ω_k(Cu) a(CuKx) E_k(CuKx), was used. The $P_k(\beta^+)$ values were, then, weighted equally to give an average value of $(26.68\pm7.50)\times10^{-4}$. The uncertainties on ω_k (Cu) a(CuKx) E_k(CuKx) were considered to be very small and were neglected in this study, and thus uncertainties on the $P_k(\beta^+)$ values are based only on the uncertainties of the N(Kx-0.511-0.511).

Ⅴ. Discussion

The result of this measurement and the earlier work[13] are presented in Table Ⅲ. Also shown are the theoretical predictions by the LS theory. The columns indicated by P(ODFS), P(LDA), and P(AKF) in the LS theory arise as follows: P(ODFS) (Optimized Dirac-Fock-Slater) is the probability calculated when Dirac-Fock-Slater wave functions are used for the parent and daughter atoms and the optimized self-consistent field potential which emerges from the daughter wave functions is used to describe the final continum electron state. P(LDA)(local density approximation) is acquired when an average Fermi momentum is used.

As seen from Table Ⅲ the experimental $P_k(\beta^+)$ values of this work are larger than in the earlier work and these experimental values are considerably larger than the LS theoretical values. The experimental $P_k(\beta^+)$ values are 5.56 times larger than P(ODFS), 4.67 times larger than P(LDA), and 4.04 times larger than P(AKF), showing that P(AKF) gives the smallest discrepancy among the theoretical $P_k(\beta^+)$ values. These factors are a little larger than the ^{58}Co $P_k(\beta^+)$ values.

In summary, the values of this measurement, as well as those values in the earlier experimental studies on the K-shell electron shakeoff in β^+ decay are considerably larger than the theoretical values. At this time it appears that more experimental work for the study of $P_k(\beta^+)$, together with the additional theoretical work is needed to try to explain the factor of 4 or 5 discrepancy between the experiment

Table Ⅲ. Probabilities for K-shell electron shakeoff in β^+ decay of ^{65}Zn($\times 10^4$)

Isotope	Experimental $P_k(\beta^+)$		LS Theoretical $P_k(\beta^+)$		
	This work	Earlier work	P(ODFS)	P(LDA)	P(AKF)
^{65}Zn	26.68±7.50	16.1±3.0	4.80	5.70	6.60

and theory.

Acknowledgments

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