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Study on the Orbital K-electron Shakeoff in β^+ Decay

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〈Abstract〉

The shakeoff probability for K-shell autoionization in the nuclear decay, $P_k(\beta^+)$, of ^{58}Co has been determined from measurements of the ***Fe K*** x-ray- 0.511 ***MeV*** positron annihilation photon-0.511 ***MeV*** positron annihilation photon triple coincidence spectrum. The x-ray absorption and detection efficiency factor has been obtained experimentally by measuring both the ***Fe K*** x-ray single spectrum and the auxiliary coincidence spectrum of the ***Fe K*** x-rays produced in ***EC*** decay with the 0.8108 ***MeV*** gamma rays. The nuclear shakeoff probability, $P_k(\beta^+)$, was found to be $(20.61 \pm 4.18) \times 10^{-4}$, which was considerably larger than the theoretical values with the factor of 2 to 3. It was suggested at this time that more experimental values of $P_k(\beta^+)$ as well as the additional theoretical work would be needed to try to explain the factor of 2 to 3 discrepancy with theory

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β^+붕괴에 의한 K-궤도 전자 Shakeoff 현상연구

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(1984. 9. 30접수)

〈요 약〉

Fe K x선 -0.511 ***MeV*** 양전자 소멸 광자 -0.511 ***MeV*** 양전자 소멸 광자간의 3중 동시 측정 스펙트럼을 관측하여 β^+붕괴에 의한 ^{58}Co ***K***-궤도 shakeoff 확률 $P_k(\beta^+)$를 결정하였다. x-선 흡수와 검출 효율 곱인자는 ***Fe K*** x-선의 단일 스페트럼 및 전자포획에서 발생된 ***Fe K*** x-선과 0.8108 ***MeV*** 감마선간의 보조 동시측정 스페트럼을 각각 측정하여 이를 shakeoff 확률계산에 이용하였다. 이 실험에서 얻은 핵 shakeoff 확률 $P_k(\beta^+)$은 $(20.61 \pm 4.18) \times 10^{-4}$ 였으며 이 값은 기존이론치보다 2내지 3배정도 큰 값이였다. 앞으로 2내지 3배의 차이를 보다 정확히 설명하기 위하여서는 보다 많은 실험치와 기존이론의 수정 등이 필요하다고 본다.

I. Introduction

Nuclear shakeoff, which is one of autoionization processes, has been the subject of theoretical and experimental study extensively in recent years.[1],[2],[3] Autoionization, in which atomic electrons are ejected during nuclear β^+ decay processes, 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 the 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. The various approaches for the theoretical understanding of the processes of autoionization associated with nuclear $\beta^{\pm}$ decay are given in several papers.[4-6] On the experimental side, work has been carried out mainly for the determination of the K-shell autoionization probability[7-11] only in nuclear β^{-} decay, $P_k(\beta^{-})$.

Recent theoretical work by Law and Suzuki[12] (LS) has brought about good agreement, typically~10%, between the theoretical and experimental values for the probability of K-shell electron shakeoff in β^{-} decay and overall better agreement than previous theories for the probability of K-shell electron in electron capture decay. This recent theoretical work, however, does not bring into agreement the theoretical and experimental values for the probability of K-shell electron shakeoff in nuclear β^{+} decay, $P_k(\beta^{+})$. A few experimental studies of $P_k(\beta^{+})$ [12-15] have been reported and have yielded values which are approximately 2 times larger than predicted by the LS theory. As suggested by LS, the final state wave function for β^{+} decay may be more complicated than previously believed or the initial and final state screening factors may be different for nuclear β^{+} decay than for nuclear β^{-} decay or electron capture. The lack of experimental values for $P_k(\beta^{+})$, compared to the large number of studies of K-electron shakeoff in nuclear β^{-} decay and electron capture, $P_k(\beta^{-})$ is due principally to the strong electron capture branches which exist in most nuclear β^{+} decay isotopes.

It was our aim in this investigation to obtain more precise experimental information on the K-shell electron shakeoff in nuclear β^{+} decay which would allow a more detailed comparison with existing experiments and theory. Led by the earlier work,[11),14)] this investigation used a Si(Li) spectrometer for x-rays, a much more complete coincidence analysis system, and an improved electronic circuitry and experimental arrangement. The ^{58}Co was chosen again for this measurement due to its relatively long half-life and to the relative ease with which one can determine x-ray absorption and detection efficiency factors from coincidence measurements between the 0.8108 *MeV* gamma ray of the first excited state of ^{58}Fe and the *Fe* *K* x-arys produced in electron capture decay.

Ⅱ. Experimental Procedures

1. ^{58}Co Source

Fig. 1 shows the decay scheme of ^{58}Co.

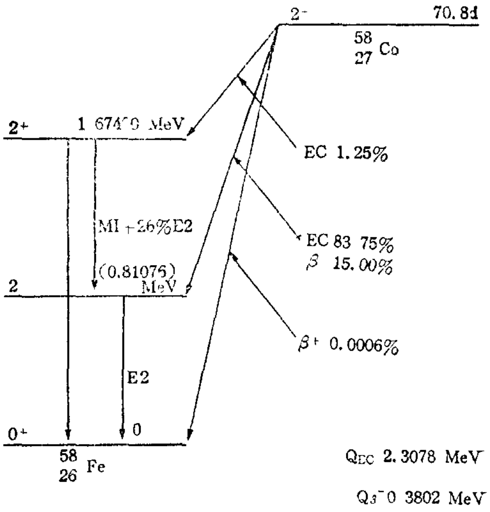

Fig. 1. Decay Scheme of ^{58}Co

with its strong (85%) electron capture (*EC*) branches and its weaker (15%) β^+ branch. The ^{58}Co source made at the University of Missouri Reactor was used in this investigation. It had an initial activity of 1.0 μC_i and decayed through about one half-life during the course of the measurement. The source was produced by the $^{58}Ni(n,p)$ ^{58}Co reaction where 14mg of natural abundance *Ni* was irradiated for 241h producing 2 μCi/mg. The source was

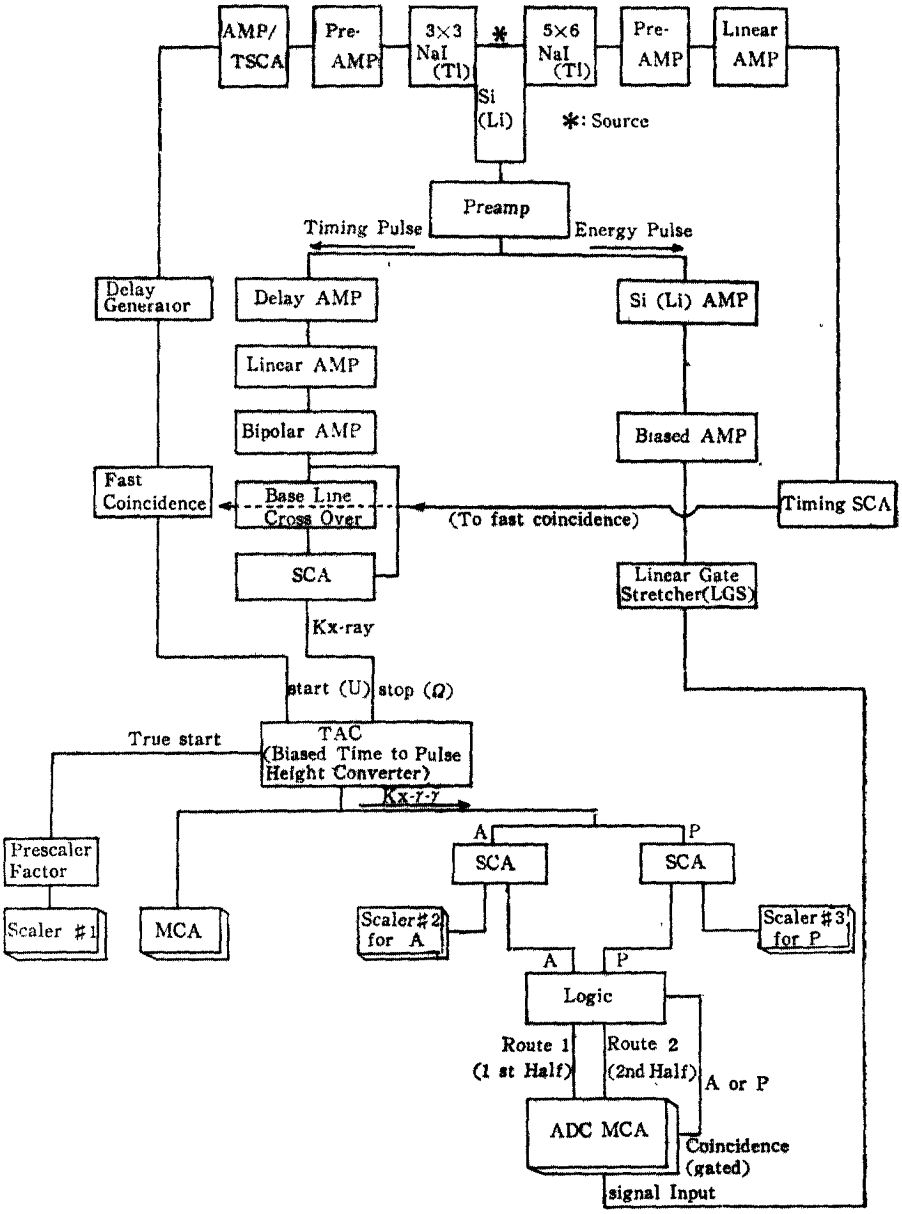

Fig. 2. Schematic diagram of detectors and circuits.

prepared by evaporating several drops of active solution on a 0.07mm thick Mylar backing. After drying, the source was covered with a second piece of Mylar and sandwiched between two 1mm thick polyethylene absorbers to absorb all β^+ locally. This combination was then placed in contact with the Be window of the *Si(Li)* detector to provide maximum efficiency for this detector.

2. Detectors

An ORTEC 7000 series *Si(Li)* x-ray detector with 4mm diameter, 4.2mm sensitive depth, 0.008mm Be window-to-detector distance, and resolution width (FWHM) of 160 eV at 5.9 *keV*, was used in the measurements. The *Si(Li)* detector used an ORTEC 739A amplifier set at 6 μsec shaping to drive the MCA input and an ORTEC 551 SCA windowing between 5.3 and 9.1 *keV* to drive the stop on the ORTEC model 457 TAC. The annihilation photons were detected with a 7.6cm diamater ×7.6cm long *NaI(Tl)* detector and a 12.7cm diameter×15.2cm long *NaI(Tl)* detector. The SCA windows selected the 0.511 *MeV* photopeak and their crossover timing outputs were fed into a fast coincidence circuit whose resolving time was set at 40 nsec.

3. Electronic Circuitry

Fig. 2 schematically shows the configuration of detectors and electronic circuitry used in this study. 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 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 multichannel analyzers recording the *K* x-ray spectra. The two *NaI(Tl)* detectors colinear with the sample was used to detect the annihilation photons subsequent to β^+ decay in most of the primary coincidence measurements, and one of them was used to detect the 0.8108 *MeV* gamma rays in auxiliary measurements used to assay detection efficiencies. The *Si(Li)* detector was used to detect the *Fe* x-rays emitted as a result of the K-shell ionization. Fig. 3 shows a typical TAC spectrum and the P- and A-SCA

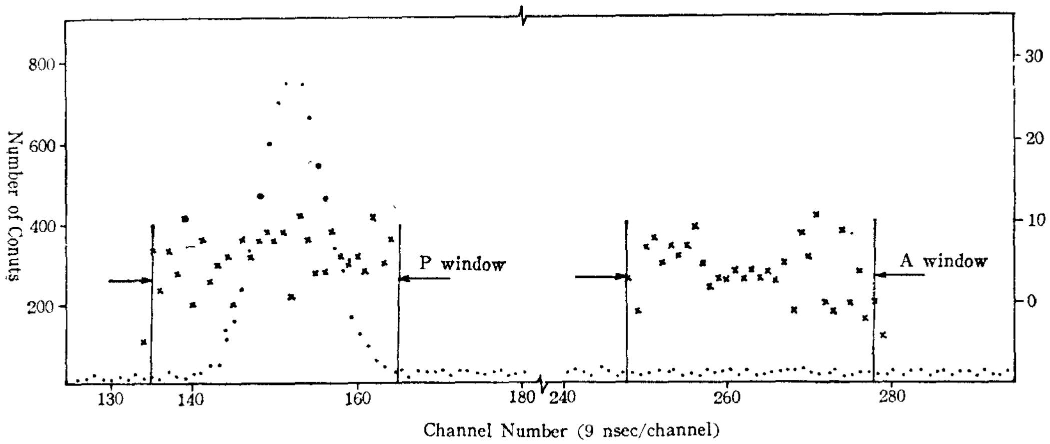

Fig. 3. TAC coincidence spectrum. Also shown are the P-and A-SCA windows(scale on right).

window settings. These window widths correspond to about 240 nsec. Since subtraction of accidental coincidences requires that the relative window widths be accurately known, periodic checks on both the P- and A-SCA widths were made during the course of experiment.

Ⅲ. Data Analysis

From the decay scheme of ^{58}Co, one realizes that the small number of experimental values of $P_k(\beta^+)$ is due principally to the experimental difficulty produced by the strong electron capture decay branches which exist in β^+ decaying process. ^{58}Co has the strong (85%) electron capture (*EC*) branches and weak(15%) β^+ branch. In determining $P_k(\beta^+)$ by detecting the *K* x-rays emitted as a result of the filling of the K-shell vacancy produced in the shakeoff process, the *K* x-rays produced in shakeoff in β^+ decay must be differentiated from these produced in *EC*.

This can be done by requiring their coincidence with the positron annihilation radiation. Thus, $P_k(\beta^+)$ was determined by the detection of the *Fe K* x-rays in coincidence with the two 0.511 *MeV* positron annihilation gamma rays. Because the K-shell ionization in *Fe* can be produced not only by shakeoff accompanying the primary β^+ decay but also by internal conversion of the 0.8108 *MeV* gamma rays, *Fe K* x-rays from the internal conversion of the 0.8108 *MeV* transition will also be in coincidence with the annihilation radiations. Since the internal conversion probabilities are quite small and relatively well known, $P_k(\beta^+)$ will be deduced from *Fe K* x-ray spectra recorded. The product of x-ray absorption and detector efficiency factors, which is useful for $P_k(\beta^+)$ calculation, can be determined by single *K* x-ray measurements of *Fe* or coincidence measurements between the 0.8108 *MeV* gamma rays and the *Fe K* x-rays produced in *EC* decay.

1. Shakeoff Probability $P_k(\beta^+)$

The probability for K-shell ionization in the nuclear β^+ decay, $P_k(\beta^+)$, can be determined by the number of *K* x-rays in coincidence with the two 0.511 *MeV* positron annihilation gamma rays. The total number of Kx$-0.511-0.511$ coincidence due to shakeoff and internal conversion recorded during a run, $N(K\text{x}-0.511-0.511)$, is given by

$$\begin{aligned} N(K\text{x}-0.511-0.511) &= N_0 f_{\beta^+}\Omega_1 E_1(0.511)E_2(0.511)E_f \\ &\quad [P_k(\beta^+)+\alpha(0.8108)] \\ &\quad \omega_k(Fe)a(Fe\ K\text{x})E_k(Fe\ K\text{x}), \end{aligned} \tag{1}$$

where N_0 is the total number of ^{58}Co decays during a run, f_{β^+} is the fraction of ^{58}Co decaying via β^+ emission, $\omega_k(Fe)$ is *Fe* K-shell fluorescence yield, $a(Fe\ K\text{x})$ is the attenuation factor due to absorption, $E_k(Fe\ K\text{x})$ is the total *K* x-ray detector efficiency, E_f is the fast coincidence efficiency, $E_1(0.511)$ and $E_2(0.511)$ are the intrinsic photopeak detection efficiencies for 0.511 *MeV* gamma rays in the two *NaI(Tl)* detectors, and Ω_1 is the solid angle subtended for the 7.6cm×7.6cm *NaI (Tl)* detector. The α (0.8108) is the K-shell internal conversion probability for the 0.8108 *MeV* transition.

Using the total number of positron annihilation radiation coincidences recorded during a run, $N(0.511-0.511)$, which can be obtained by

$$\begin{aligned} N(0.511-0.511) &= N_0 f_{\beta^+}\Omega_1 E_1(0.511) \\ &\quad E_2(0.511), \end{aligned} \tag{2}$$

and rearranging Eq. (1), the shakeoff probability, $P_k(\beta^+)$, is given as follows:

$$\begin{aligned} P_k(\beta^+) &= \frac{N(K\text{x}-0.511-0.511)}{N(0.511-0.511)} \\ &\quad \cdot \frac{1}{\omega_k(Fe)\ a(Fe\ K\text{x})\ E_k(Fe\ K\text{x})} \\ &\quad -\alpha(0.8108) \end{aligned} \tag{3}$$

2. X-ray Absorption and Detection Efficiency Factors:

The x-ray absorption and detection efficiency factors, $\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x})$, can be determined both by singles measurements using the known decay rate of the ^{58}Co source or by auxliary coincidence measurements of the *Fe K* x-rays produced in *EC* decay with the 0.8108 *MeV* gamma rays.

(1) Single *K* x-ray spectrum

The total number of *Fe K* x-rays detected with the *Si(Li)* detector during a run, $N(K\mathrm{x})$, is given by

$$N(Fe\ K\mathrm{x})=N_0[f_{EC1}(K/T)_1+f_{EC2}(K/T)_2]\,\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x}) \quad (4)$$

where N_0 is the total number of decays during the singles run, $(K/T)_1$ and $(K/T)_2$ are the K-shell-to-total ratios for *EC* to the 1.6747 and 0.8108 *MeV* levels, respectively, and f_{EC1} and f_{EC2} are the fractions of ^{58}Co decays which proceed via *EC* to the 1.6747 and 0.8108 *MeV* levels.

Rearranging Eq. (4) gives the x-ray absorption and detection efficiency factor product,

$$\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x})=\frac{N(Fe\ K\mathrm{x})}{No}\cdot\frac{1}{f_{EC1}\ (K/T)_1+f_{EC2}(K/T)_2} \quad (5)$$

(2) Coincidence measurement

In order to determine the $\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x})$ product of Eq. (3), auxiliary coincidence measurements were taken for each run utilizing the *Fe K*x ray-0.8108*MeV* gamma coincidences in the 83.75% electron capture branch of the ^{58}Co decay. With the source in exactly the same position as for the *Fe K*x ray-0.511-0.511 coincidence runs, the SCA on the 12.7cm×15.2cm *NaI(Tl)* detector was adjusted to window on the 0.8108 *MeV* photopeak, which was taken on the only input requirement to the fast coincidence circuit. The total number of 0.8108 *MeV* gamma rays in the window, $N(0.8108)$, recorded with the *NaI(Tl)* detector is given by

$$N(0.8108)=No[2f_{EC1}f+f_{EC2}+f_{\beta^+}]\,\Omega_2E_2(0.8108), \quad (6)$$

where f is the fraction of decays of 1.6747 *MeV* level which proceed through the 0.8108 *MeV* level and Ω_2 is the solid angle subtended by the 12.7cm×15.2cm *NaI(Tl)* detector. The multiplicative factor of 2 on the $f_{EC1}f$ term arises as follows: The window of the *NaI(Tl)* detector centered on the 0.8108 *MeV* gamma ray will allow detection with full peak efficiency of the 0.8639(=1.6747-0.8108) *MeV* gamma ray which precedes the 0.8108 *MeV* gamma ray in the decay; both gamma rays will also be in coincidence with the *Fe K* x-rays produced in this *EC* branch. Hence either of the two gamma rays will produce a coincidence so the $f_{EC1}f$ term is nearly doubled. The total number of coincidences records between the *Fe K* x-rays in the *Si(Li)* detector and the 0.8108 *MeV* gamma rays in the 12.7 cm×15.2cm *NaI(Tl)* detector during an auxiliary coincidence measurement, $N(K\mathrm{x}-0.8108)$, is given by

$$N(K\mathrm{x}-0.8108)=No[2f_{EC1}f(K/T)_1+f_{EC2}(K/T)_2]\,\Omega_2E_2(0.8108)\,\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x}) \quad (7)$$

Taking the ratio of Eq. (6) to Eq. (7) and rearranging then gives $\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x})$ as follows:

$$\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_k(Fe\ K\mathrm{x})=\frac{N(K\mathrm{x}-0.8108)}{N(0.8108)}\cdot\frac{1}{K/T}\cdot\frac{2f_{EC1}f+f_{EC2}+f_{\beta^+}}{2f_{EC1}f+f_{EC2}} \quad (8)$$

where K/T is taken for both $(K/T)_1$ and $(K/T)_2$ and the bracketed factor is 1.176.

Ⅳ. Results

1. K x-ray Single Spectrum

Fig. 4 shows the *Fe K* x-ray single spectrum measured with the *Si(Li)* detector. Two x-ray

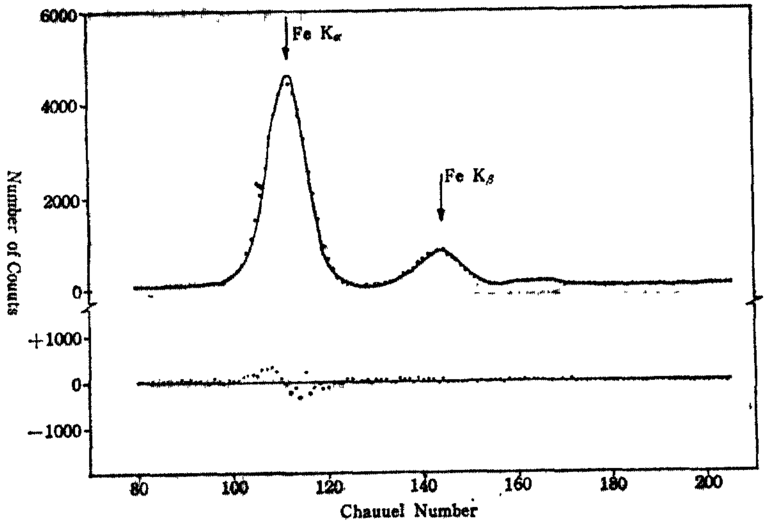

Fig. 4. Fe K x-ray single spectrum with computer fitted components. Also shown is the difference between the measured and computer fitted spectra.

Table. 1. Data and constants used in analysis

data		constants			
No (counts/sec)	N(*Fe K*x) (counts/sec)	f_{EC1}	f_{EC2}	$(K/T)_1$	$(K/T)_2$
2.3889×10^4	1.4053×10^1	0.0125 (1.25%)	0.8375 (83.75%)	0.908	0.909

peaks appearing on the spectrum are $K\alpha$ and $K\beta$ x-rays of energy 6.40 and 7.06 *keV* emitted from *Fe*, respectively. The solid line on the spectrum is the computer fitted components, which was used to calculate the number of K x-rays detected. Also shown is the difference spectrum between the experimental and computer fitted spectra.

The number of *Fe K* x-rays obtained in this experiment was found to be 5.6211×10^3 counts in 4000sec experimental run, which gives the *Fe K* x-ray counting rate 1.405×10^1 counts/sec. Table 1 shows the data and constants necessary for the calculation of the x-ray absorption and detcetion efficiency factors. Using the data and constants in Table 1, the x-ray absorption and detection efficiency factor product is calculated to be

$$\omega_k(Fe)\ a(Fe\ K\mathrm{x})\ E_t(Fe\ K\mathrm{x}) = (7.6100\pm0.031)\times10^{-4}$$

2. Kx-0.8108 Coincidence Spectrum

Since the positron decay of ^{58}Co proceeds either to the ground state or to the 0.8108 *MeV* first excited state of ^{58}Fe in the 83.75% electron capture branch of the ^{58}Co decay, the K x-rays emitted from ^{58}Fe can be measured in coincidence with the 0.8108 *MeV* gamma rays. The Kx-ray-0.8108 *MeV* gamma ray coincidence spectrum measured is shown in Fig. 5, where *Fe* $K\alpha$ and $K\beta$ x-ray peaks appeared. By recording accidental and true-plus-accidental coincidences concurrently by use of both the "accidental" and "prompt" single channel analyzer (A and P SCA) on the output from TAC, the P and A coincidence

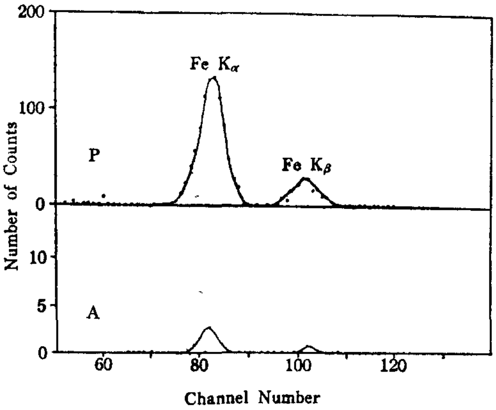

Fig. 5. ***Fe K*x-0.8108 coincidence spectrum. The graph shows the prompt(P) and accidental(A) coincidence spectra with the least squared computer fitted components.**

spectra were routed to different memory halves of the multichannel analyzers recording the *Fe K* x-ray spectra. The upper figure in Fig. 5 shows the prompt (*P*) coincidence spectrum and lower figure shows the accidental (*A*) coincidence spectrum. As seen in Fig. 5 the number of *K*x-0.8108 accidental coincidences is found to be rather less compared to the prompt coincidence counts.

The difference between the counts of prompt coincidence and the accidental coincidence gives the number of counts in true coincidence of *K*x-0.8108 coincidence, which was found to be 3.8963×10^3 counts/hr. The counting rate of 0.8108 *MeV* gamma rays of ^{58}Fe with the same source and the same position as for the *K*x-0.8108 coincidence run was measured as 6.1320×10^6 counts/hr, after being corrected by its background. Using the counting rates of 0.8108 *MeV* gamma rays and *K*x-0.8108 coincidence *K* x-rays, and constants given in Table 1, the x-ray absorption and detection efficiency factor gives

$$\omega_k(Fe)\ a(Fe\ Kx)\ E_k(Fe\ Kx)=8.2114\times10^{-4}$$

3. *K*x-0.511—0.511 Coincidence Spectrum

The *K*x-0.511—0.511 prompt(*P*) and accidental(*A*) coincidence spectrum with the least squared computer fitted components are shown in Fig. 6. Also shown is the difference spectrum between the experimental and fitted spectrum. The Ni Kx-rays seen in the prompt spectrum are due to Ni fluorescence in the residual ^{58}Ni from the (np) reaction. The coincidence spectrum, 0.511—0.511, between the two positron annihilation gamma rays subsequent to β^+ decay was measured by the two *NaI(Tl)* detectors colinear with the source, where the same source and the same position as for the *K*x-0.511—0.511 coincidence run were used. Table 2 shows the data obtained in the *K*x-0.511—0.511 coincidence run as well as the data in the 0.511—0.511 coicidence run. The N_P and N_A represent the total number of prompt and accidental *Fe K* x-ray coincidences, respectively, recorded during a run, and *N* is

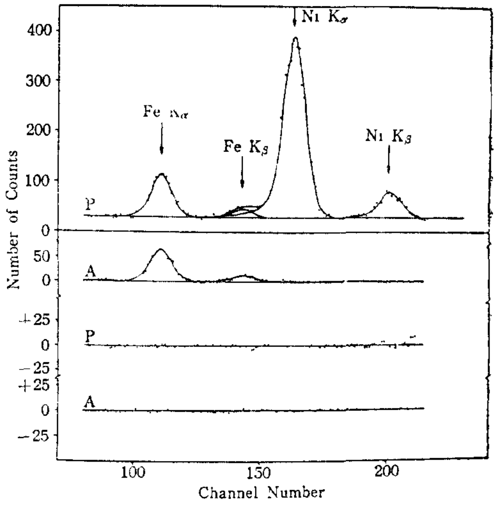

Fig. 6. *K*x-0.511—0.511 coincidence spectrum. The prompt(P) and accidental(A) coincidence spectrum with the computer fitted components are shown. The figure also shows difference spectrum between the experimental and fitted spectrum.

Table 2. Data obtained from Kx-0.511—0.511 and 0.511—0.511 coincidences

Run number	Time(hour)	$N(K$x-0.511—0.511)			N(0.511—0.511) (×10^{+6})
		N_P	N_A	N	
1	113.3	311	220	91	52.46
2	153.3	409	291	118	70.29
3	225.0	599	430	169	102.13
4	295.4	783	557	226	132.65
5	389.5	973	735	238	171.70

the difference the between N_P and A_A.

4. Shakeoff Probability $P_k(\beta^+)$

The shakeoff probability for K-shell ionization in the nuclear β^+ decay, $P_k(\beta^+)$, of ^{58}Co can be calculated by Eq. (3) using the experimental measured numbers for *Fe K* x-rays in Kx-0.511−0.511 coincidence and also the positron annihilation gamma rays in 0.511−0.511 coincidence. Table. 3 shows the data necessary for the calculation of the probability, $P_k(\beta^+)$, as well as the values of $P_k(\beta^+)$ obtained for each run. For each of the five Kx-0.511−0.511 coincidence run, the $\omega_k(Fe)$ $a(Fe\ K\mathrm{x})$ $E_k(Fe\ K\mathrm{x})$ product values obtained both by the *Fe K* x-ray single spectrum and the Kx−0.8108 coincidence spectrum were used. The value of the K-shell internal conversion probability for the 0.8108 *MeV* transition, $\alpha(0.8108)$ which was appeard in Eq. (3) was very small and was neglected. The two separate methods, for determining the x-ray obsorption and detection efficiency factors, $\omega_k(Fe)$ $a(Fe\ K\mathrm{x})$ $E_k(Fe\ K\mathrm{x})$, yielded values consistent to 8%, which makes $P_k(\beta^+)$ values consistent to about 8% for each run. The $P_k(\beta^+)$ values were weighted equally to give an average value of $(20.61 \pm 4.18) \times 10^{-4}$. The uncertainties on the individual $P_k(\beta^+)$ values are based on the uncertainties on $N(K$x-0.511−0.511). The uncertainties on $\omega_k(Fe)$ $a(Fe\ K\mathrm{x})$ $E_k(Fe\ K\mathrm{x})$ were considered to be very small and were neglected in this study.

Ⅴ. Discussion

The results of this measurement and the theoretical prediction of LS theory for shakeoff in ^{58}Co decay are presented in Table 4. 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 function is used to describe the final continuum electron state. P(LDA) (local density approximation) is acquired when the Fermi momentum is calculated from the local electron density and P(AKF) (average Fermi momentum) is acquired when an average Fermi momentum is used.

As seen from Table 4, the experimental values are considerably larger than the theoretical values. The experimental value $P_k(\beta^+)$ is 3.1±0.6 times larger than P(ODFS), 2.6±0.5 times larger than P(LDF), and 2.2±0.5 times larger than P(AKF), showing that P(AKF) gives the smallest discrepancy in all cases. These factors are very consistent, except for P(ODFS), with ^{64}Cu $P_k(\beta^+)$ values where the factors are 2.3 and 1.9, respectively.

In summary, the results for K-shell ionization in the β^+ decay of ^{58}Co are generally consistent with the results of ^{64}Cu in that

Table. 3. Data used for $P_k(\beta^+)$ calculation and $P_k(\beta^+)$ values

Experiments	$N(Kx\text{-}0.511-0.511)$ / $K(0.511-0.511)(\times 10^{+6})$	$P_k(\beta^+)(\times 10^{+4})$	
		using the Kx x-ray single spectrum	using Kx-0.8108 coincidence spectrum
1	1.71±0.44	22.47±5.78	20.83±5.36
2	1.69±0.38	22.21±4.99	20.58±4.63
3	1.65±0.31	21.68±4.07	20.09±3.78
4	1.71±0.28	22.47±3.68	20.83±3.41
5	1.38±0.24	18.13±3.15	16.81±2.92
Average $P_k(\beta^+)$		21.39±4.33	19.83±4.02

Table. 4. The experimental result of this study and theoretical predictions of LS for $P_k(\beta^+)$

Isotope	Experimental $P_k(\beta^+)$ $(\times 10^4)$	LS theoretical predictions$(\times 10^4)$		
		P(ODFS)	P(LDA)	P(AKF)
^{58}Co	20.61±4.18	6.70	7.96	9.22

both isotopes showing a larger probability than predicted by the LS theory. At this time it appears that more experimental values of $P_k(\beta^+)$ as well as the additional theoretical work is needed to try to explain the factor of 2 to 3 discrepancy in experiments.

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