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M. Sakai, H. Kawakami, K. Omata, I. Sugai, I. Katayama,
S. Shimizu, K. Horie, and T. Miura

Center for Nuclear Study (CNS)

Graduate School of Science, the University of Tokyo
Wako Branch at RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Correspondence: cnsoffice@cns.s.u-tokyo.ac.jp

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M. Sakai,[1,*] H. Kawakami,[1,†] K. Omata,[1,†] I. Sugai,[1,†] I. Katayama,[1,†] S. Shimizu,[2] K. Horie,[2] and T. Miura[3]

[1] *High Energy Accelerator Research Organization, Tanashi Branch, Tanashi-shi, Tokyo 188-8501, Japan*

[2] *Department of Physics, Graduate School, Osaka University, Toyonaka, Osaka 560-0043, Japan*

[3] *High Energy Accelerator Research Organization, Oho 1-1 Tsukuba 305-0801, Japan*

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A narrow line was observed in the coincidence time spectrum of positrons and electrons moving with a momentum of 330.3keV/c along the central trajectory of a large β-ray spectrometer. The observed cross section agrees well with predictions based on earlier data.

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I. INTRODUCTION

A peak like structure was observed in the coincidence spectrum between positrons and electrons emitted from the back of a thorium target irradiated by positrons from a ^{68}Ge-^{68}Ga-^{68}Zn (E_{max}=1.90MeV) source by Oak Ridge National Laboratory(ORNL) in 1986 [1]. The authors speculated that the peak resulted from the e^+e^- pair decay of a hypothetical neutral particle generated in the target. They used thick targets of 40−60mg/cm^2 which not only deteriorated the energy resolution leading to a measured mean energy loss of 30−50keV but which also produced a nearly complete loss of the direction information of the decay leptons. Consequently the measured spectrum was obtained with a wide energy binning of 6.7keV and the peak was claimed for a slight positive excursion with respect to a large background with an energy of around 340keV−345keV and a yield of 500±200 events. Because of the relatively low statistics and the far-reaching theoretical implications the ORNL results have been met with considerable skepticism by the nuclear physics community. Moreover, experiments similar to that of ORNL at Frankfurt [2] and Argonne [3] produced inconsistent results. We have conducted a series of experiments for confirming the reported phenomena in the period from 1986 to 1992 [4–7] at the Institute for Nuclear Study, University of Tokyo (INS). We employed positron activities of ^{118}Te-^{118}Sb-^{118}Sn (E_{max}=2.66MeV) [5, 6] and ^{82}Sr-^{82}Rb-^{82}Kr (E_{max}=3.37MeV) [7]. Since the observation of a positron-electron coincidence peak would imply the existence of mono-energetic electrons emitted simultaneously with equal-energy positrons from the irradiated target we searched for the relevant electrons in singles with the use of the INS double focusing air-core β-ray spectrometer (ρ=75cm). To obtain high resolution spectra we used a rolled thorium metallic foil with a thickness of 1.4 mg/cm^2. Placing it flat against the positron source and setting it at the source position, we searched for the peak. As the spectrometer has an almost constant resolution along the focal plane, we can take momentum spectra spectrographically in a range of 6.0% of $\Delta p/p$ with a position sensitive proportional counter set on the focal plane. According to the ORNL result we set the magnetic field to the energy of 340keV and accumulated a large amount of events for a long measuring time. We observed a clear narrow line on the spectrogram in every series of experiments. The weighted mean energy and the cross section are determined 330.3±0.4 keV and 149[1±0.13 (stat) ±0.25(syst)] mb, respectively [4]. The small experimental errors indicate a good reproducibility and an internal consistency between the different experiments. We calculated the number of genuine events expected from the ORNL experiment with the use of our cross section. It yielded 350[1 ± 0.13 (stat)± 0.25(syst)] counts that can be compared with the reported yield of 500±200 counts. This close agreement may reflect a common underlying process with the ORNL peak.

II. e^+e^- COINCIDENCE EXPERIMENT

A. Experimental setup

The e^+e^- coincidence experiments were performed by attaching a positron chamber on the opposite side of the source chamber of the iron-free β-ray spectrometer employed in the previous experiments [5–7]. A schematic diagram of the new setup is illustrated in Fig. 1. We used the same species of a β^+ activity of ^{82}Sr as used in the previous experiment [7]. It was produced at Los Alamos via spallation of molybdenum and subsequent chemical separation. Its characteristic is a separated Sr(II) in 0.1mole HCl of 0.09ml that contained both ^{82}Sr and ^{85}Sr with initial activities of 37MBq and 59MBq, respectively. We prepared the source by depositing the radioactive liquid on a 3mm×16mm area of a 1.5 μm polyester membrane after the lapse of $1.85T_{1/2}(^{82}\mathrm{Sr})$. To keep the di-

*Present address, Center for Nuclear Study, University of Tokyo, 2-1 Hirosawa, Wako, Saitama 351-0198 Japan

†Present address, High Energy Accelerator Research Organization, Oho 1-1 Tsukuba 305-0801, Japan

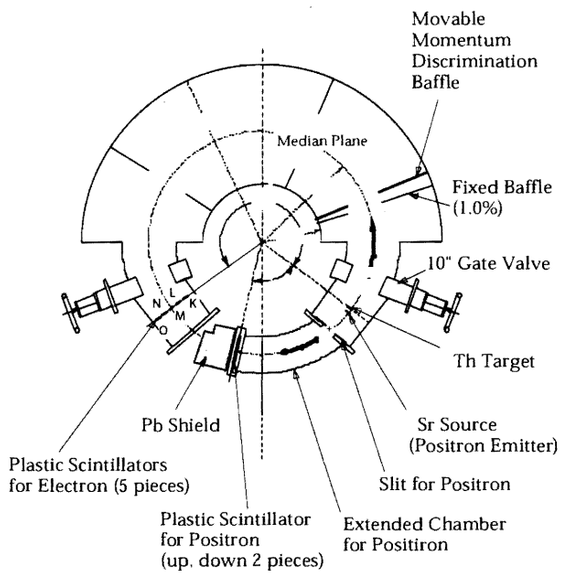

FIG. 1: Schematic diagram of the experimental setup.

rection memory we used a rolled thorium metallic foil of 0.8mg/cm^2 with the same size as the source and put it on top of the source with a separation of about 0.5mm. The source/target foils were placed in the source chamber with the thorium foil at the source position. The electron baffle slit for a momentum resolution of $\Delta p/p$=1.0% was made in accordance with the iso-aberration contour [8] to optimize the transmission which was found Ω_-=1.2%/4π. As the defining radial aperture angle of ϕ_r varies on the position of the contour curve, we averaged it and found 10.0°. The electrons were detected by a counter array consisting of five plastic scintillator paddles, 2mm thick, 15mm wide and 100mm long, termed K, L, M, N and O in the order of increasing momentum. They were horizontally placed in the focal plane of the spectrometer next to each other with a gap of 10mm between the paddles. The center counter M was arranged to be on the central trajectory. The width of the paddle corresponds to a momentum window of 0.5% of $\Delta p/p$. The flight path length from the target to the central counter is 333.2cm. To detect the positrons two plastic scintillators, A(upper) and B(lower), 2mm thick, 100mm high and 160mm wide, were vertically placed (one above the other) on the deflection angle of 60° and installed in the positron chamber. At the entrance of the chamber a 30mm thick lead shield with a slit of 62mm high and 37 mm wide at the center was placed at a distance of 170mm from the target to the outer face of the shield.. The slit assured an effective solid angle of Ω_+=0.63%/4π and the defining radial aperture angle of ϕ_r is 6.2°. The length of the central trajectory of the positrons from the target to the detector was 78.5cm.

B. Measuring procedure

In this setup the positrons are subjected to the same magnetic field as the electrons. The predicted e^+e^- pairs would fly off back-to-back and propagate along the central trajectory and hit the counters. The arrival time and pulse height of each counter were registered event by event. The difference in time-of-flight of the e^+e^- pair was measured with a TDC (time to digital converter) with a dynamic range of 200ns with the electrons supplying the start and the positrons, the stop signals. If the searched for 180° correlated equal-energy lepton pair does exist we would expect a sharp peak in the time spectrum because relevant coincident e^+e^- pairs have the same time-of-flight difference. The spectrum was displayed in 2000channels with a time bin size of 0.1ns. A delay line of 100ns was inserted in the positron circuit to displace the coincidence spectrum by 1000channels. The coincidence time spectrum was taken by setting gates on the pulse height spectra. The location of peak, $P(E)$, of the coincident E-keV pairs produced by M electron and A positron counters is given in units of channel (0.1ns) by

$$P(E) = 1000 + [T_+(\mathrm{A}) - T_-(\mathrm{M})] + [t_+(E) - t_-(E)], \quad (1)$$

where T_+(A) and T_-(M) are the delay times of pulses in the cable between the output of the scintillator and the input of the electronics for the A positron and the M electron detector and $t_+(E)$ and $t_-(E)$ stand for the time of flight of leptons from the target to the detector, respectively. The first part of Eq.(1), $1000 + [T_+(A) - T_-(M)]$, is the displacement of the spectrum caused by the instrumental delay time so that it is constant and independent of lepton energy. The time spectrum is to be produced by convoluting the time distribution of $[t_+(E) - t_-(E)]$. The spectra are calibrated relative to the (A, M) coincidence spectrum. The procedure for evaluating the intensity and peak-shift normalization factors will be discussed in the next subsection of III.B. In the following discussion we employ the notation of X× Y for the coincidence time spectrum produced from the experimental pulse height × pulse height matrix of X electron and Y positron counters.

III. EXPERIMENTAL RESULTS

A. 762.2-keV setting

For calibration purposes and to check the operation of the whole setup we first measured the 762.2-keV coincidence spectrum. It results from coincidences between the 762.2-keV conversion electrons of the ground state transition from the 776.5-keV first excited state in ^{82}Kr and the decay positrons from ^{82}Rb, the daughter element of ^{82}Sr, feeding this state. The relevant decay scheme is presented in Fig. 2. Spectra were taken by setting the magnetic field to 762.2 keV. Pulse height spectra of coincident

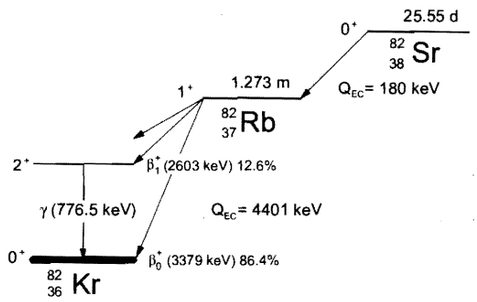

FIG. 2: Partial decay scheme of ^{82}Sr.

leptons of M, A and B are shown in Figs. 3 (a), (b) and (c). M has a narrow profile while A and B exhibit a wide profile. The difference is caused by the degraded resolution of the positron scintillator due to its large dimension and by the large amount of background of positrons and photons arriving through the wide acceptance angle of the counter. The coincidence time spectrum was taken by setting gates on the pulse height spectra as indicated in Fig. 3. As shown in (d) the coincidence peak of M×B appeared in the left hand side of that of M×A. It implies T_+(A) > T_+(B) and the shift of Δ_+(B)=T_+(A)−T_+(B) was determined to be 16±1channels. The sum spectrum of M×(A+B) was constructed by shifting M×B by Δ_+(B) to the M×A side and adding both spectra together. The resultant spectrum is shown in (e). The location and width of the peak are determined to be 1022channels and 36channels, respectively.The unknown quantity of [T_+(A)−T_-(M)] in Eq.(1) was derived from the observed P(762)=1022chanels by substituting t_+(762)=2.7ns and t_-(762)=12.15ns into Eq.(1). This yields [T_+(A)−T_-(M)]=116.5channels. With this value Eq.(1) is re-written as:

$$P(E) = 1116.5 + [t_+(E) - t_-(E)]. \qquad (2)$$

Here we have used 2.7ns in place of 2.86ns for t_+(762) because the Monte Carlo simulations revealed that the t_+ distribution has a peak at 2.7ns with FWHM=0.3ns due to the large contribution of higher energy positrons passing through the wide momentum window. Then the location of the coincidence peak of the searched for lepton pairs can be estimated with the formula of Eq.(2). Substituting t_+(330.3)=3.3ns and t_-(330.3)=14.0ns into Eq.(2) we obtained P(330.3)=1009.5channels.

B. 330.3-keV and 356.6-keV settings

The coincidence peak of correlated e^+e^- pairs was searched for by setting the magnetic field to the reported energy of 330.3 keV [5–7]. In addition background spectra were taken by increasing the magnetic field by 5%, which corresponds to 356.6 keV. Henceforth we denote the principal and the background measurement as Pl and Bk, respectively. The total number of radioactive decays of ^{82}Sr during the measurements of Pl and Bk was 7.0×10^{12} and 4.2×10^{12}. The pulse height spectra of coincident leptons of Pl are shown in Fig. 4 (a), (b), (c), (d), (e), (f) and (g) for the K, L, M, N, O, A and B, respectively. Since the K spectrum (a) had a poor energy resolution, the data associated with paddle K were discarded in the following analyses. Coincidence time spectra were taken with gates indicated in Fig. 4 and sum spectra were constructed with the use of the same Δ_+(B) as determined in the preceding subsection. Resultant sum spectra were normalized to M×(A+B) by the counting efficiency of each counter which was deduced by the total counts of the pulse height spectrum. The spectral shift relative to M of each paddle counter was determined by superimposing each spectrum on the M spectrum. The resultant shifts were cross checked with the use of the corresponding Bk spectra. The adopted normalization factors were L(1.04; 0), M(1.0; 0), N(1.10; −16) and O(1.38; −4), where the first figure of the parentheses is the intensity factor and the second one the relative shift, respectively. The spectra calibrated relative to the standard M spectrum together with M are presented in Fig. 5 (a), (b), (c) and (d) denoted by L, M, N and O, respectively.

Every spectrum presents a similar spectral structure composed of a broad peak and a roughly constant background on both sides. A nearly equal intensity of the bump in every spectrum implies that electrons arrive at the focal plane with a uniform intensity in a wide momentum range due to the same momentum acceptance of each paddle. We postulated that the peaks result from Compton electrons scattered out from the thorium target by the 776.5-keV gamma rays coincident with the decay positrons. We roughly estimated the intensity of Compton electrons taking into account the instrumental configuration and employing the cross section of Compton scattering of 20.8 mb/electron.sr at the 35° scattering angle, at which the incident 776.5-keV γ-ray produces a 330.3-keV Compton electron. We obtain 315 events which can be compared with the experimental intensity of 360 events which was deduced from the averaged Compton peaks of L, and O spectra. The flat component could consist mainly of accidental coincidences between intense, scattered 498.8-keV conversion electrons of the 514-keV transition of the contaminant ^{85}Rb and β-decay positrons or scattered photons. To verify this assumption we took a spectrum with the magnetic field set to 567keV that cuts out all electrons associated with the relevant conversion electrons. Consistent with this interpretation the flat part observed in the spectrum is negligible.

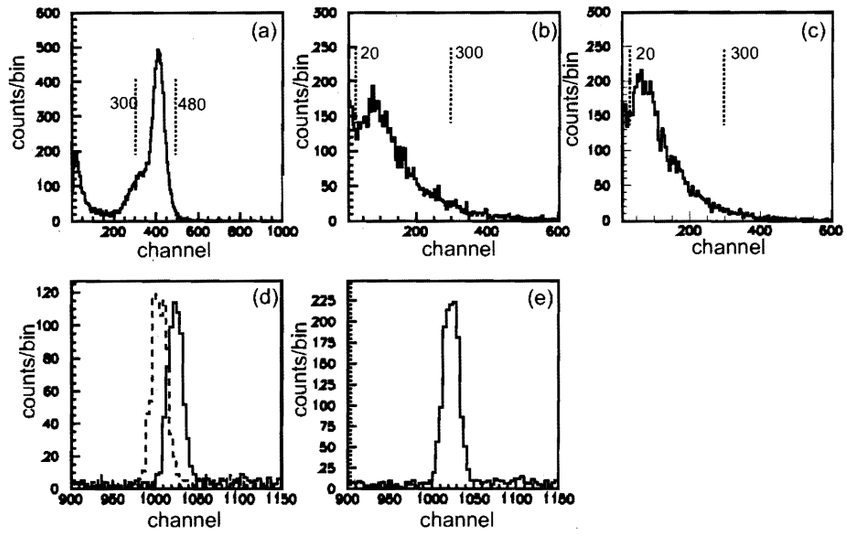

FIG. 3: Spectra obtained with the 762.2-keV setting. (a), (b), and (c) are pulse height distributions of the M, A, and B plastic scintillator paddles. The employed gates are indicated as vertical lines. (d) and (e) are time spectra. (d) presents an overlap spectrum of M×A (solid line) and M×B (dotted line). From this $\Delta_+(\mathrm{B})=T_+(\mathrm{A})-T_+(\mathrm{B})=16$channels was determined. (e) is the sum spectrum of M×(A+B) with the M×B spectrum shifted by 16channels. The spectra (d) and (e) are presented with a bin size of 4channels.

IV. SEARCH FOR THE EXPECTED PEAK

A. Analysis of spectra

The coincident peak of the correlated lepton pairs, even if it does exist, would not be observed due to a large amount of the same energy electrons produced by the Compton scatterings as discussed in the end of the preceding subsection. Therefore we tried to uncover the buried genuine peak by subtracting the adjacent L and O spectra from the center M spectrum because these spectra consist uniquely of background pulses according to the following statistical calculation.

On the assumption that the electron accompanies a 180° correlated positron partner the momentum distribution of the relevant electrons could be deduced with the use of the defining radial aperture angle of ϕ_r=6.2° of the positron baffle together with the iso-aberration contour [8] where we take into account that the positron instead of the electron baffle slit defines the momentum resolution due to the 180° correlation property and the condition of $\Omega_+ < \Omega_-$ It was found 0.5%. The statistical evaluation shows that the electrons with such a resolution only contribute to the M peak. The difference spectra of $M-L$ and $M-O$ show a bar like peak as presented in the upper panels of Fig. 6. Contrary to the statistical estimation we noticed a weak peak in the $N-L$ and $N-O$ spectra as presented in the lower panels. They have a strong resemblance to the spectra of the upper panels. The peak width of the upper and the lower panel is 16 and 20channels, respectively. The remarkable resemblance of all the peaks between each others could provide a proof that all the peaks are originated with the same production mechanism and the weak peaks would be authentic and not spurious. As the L and O spectra are independent each other we made the sum spectrum of $M-(L+O)/2$ and $N-(L+O)/2$ to improve the statistical level. The averaged intensity and the ratio are 201±23, 124±25 and 1.62 for M, N and M/N, respectively. They are shown in Fig. 7. Narrow peak-like structures with a weak intensity appearing in the panels could be spurious due to its narrowness. For reference the corresponding Bk sum spectra are also presented in the lower panels. The experimental points scatter on the zero line and any statistically significant peak did not be observed. The properties of the observed peak are summarized in Table I.

TABLE I: Summary of the experimentally observed correlated peaks

	Location (channels)	Width (channels)	Intensity(counts)
$M-L$	1012	16	198±33
$M-O$	1012	16	204±33
$N-L$	1010	20	113±36
$N-O$	1010	20	134±36

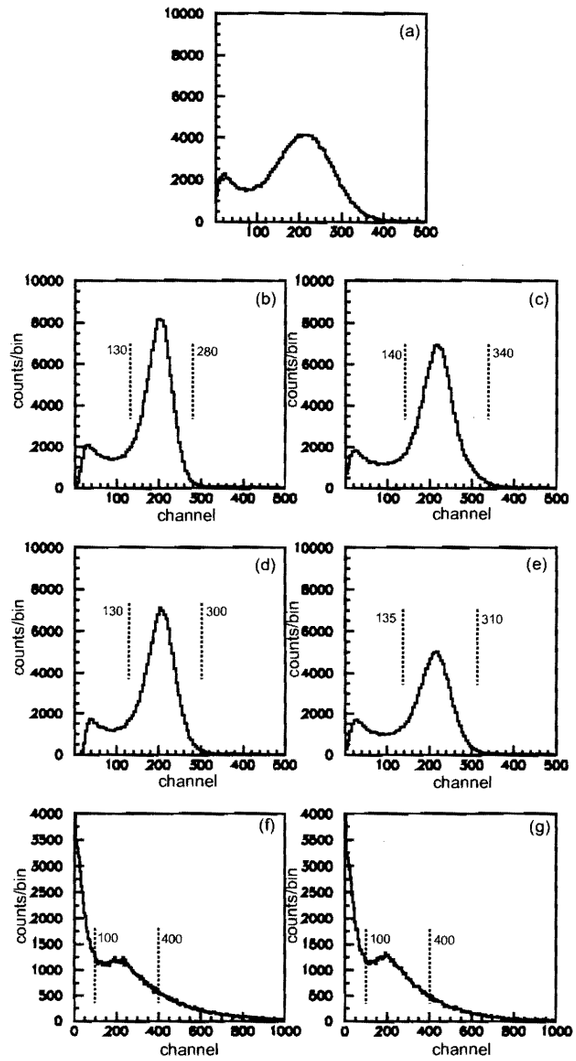

FIG. 4: Pulse height spectra for the 330.3-keV setting. (a), (b), (c), (d) and (e) present the spectra of the K, L, M, N and O electron paddle counters. (f) and (g) are the spectra of the A and B positron counters. Because the K spectrum (a) has exclusively a poor energy resolution, the data associated with the paddle K were discarded for the following analyses. In each spectrum the employed gate position is indicated. The spectrum is presented with a bin size of 2channels.

1. *Location of peak*

The observed peak location is very close to the predicted 1009.5channels. It indicates that the lepton pairs fry back-to-back on the central trajectory with a momentum of 330.3keV/c (cf. III.A).

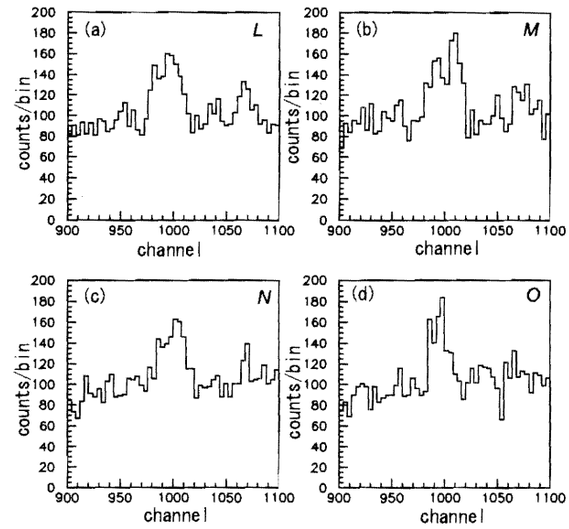

FIG. 5: Spectra calibrated in intensity and peak shift to the M spectrum. Time spectra of (a), (b), (c) and (d) denoted by L, M, N, and O result from the corresponding paddle counter. They are presented with a bin size of 4channels.

2. *Profile of time spectrum*

Although a mono-energetic electron beam takes naturally a sharp momentum distribution its time-of-flight spectrum spreads because the flight length from the source to the detector depends considerably on the emitting angle. It is formulated as

$$l = l_0 + 4\rho\phi, \tag{3}$$

where l_0 and l are the length of the trajectory of electrons emitted from the target on the direction of the central trajectory and out of it and ϕ and ρ are the radial emission angle and the radius of curvature, respectively [9]. From Eq.(3) we can deduce the following formula

$$d\phi = dl/4\rho. \tag{4}$$

As dl and $d\phi$ correspond to the unit of t_- abscissa and to the unit of intensity ordinate, respectively, the formula implicates that the time-of-flight spectrum takes a rectangular form and the width of the present case is formulated as:

$$W = 20\phi_r/\beta. \tag{5}$$

The width of the time-of-flight spectrum of the correlated electron beam is to be deduced by substituting $\phi_r = 6.2^\circ$ of the rectangular aperture of the positron baffle (cf. IV A) into Eq.(5) and found 27channels. As the time-of-flight spectrum of t_+(330.3) takes a sharp line due to the mono-energetic property and the short trajectory, the coincidence time spectrum produced by convoluting the

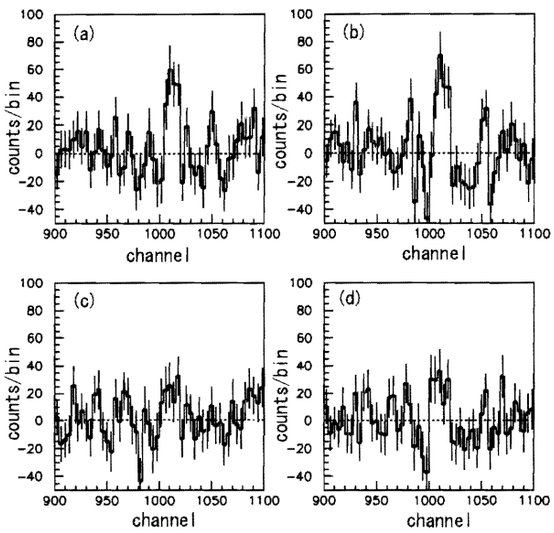

FIG. 6: Subtracted spectra of $M-L$, $M-O$, $N-L$ and $N-O$ for the Pl setting. The former two spectra (a) and (b) are presented in upper panels and the latter two (c) and (d) in lower panels. A peak is observed in $M-L$, $M-O$, $N-L$ and $N-O$ for each spectrum. They are presented with a bin size of 4channels.

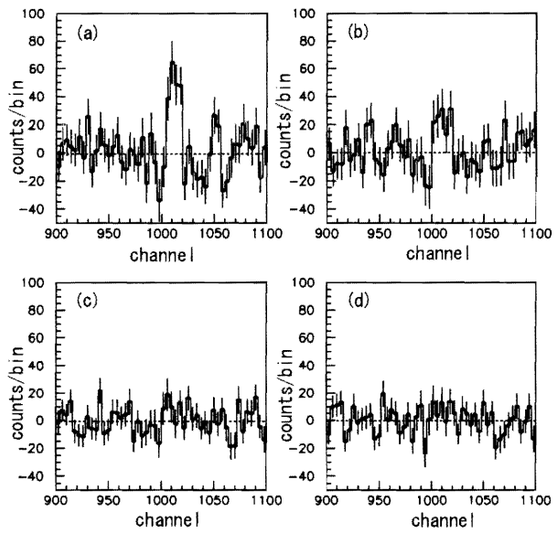

FIG. 7: Sum spectra of $M-(L+O)/2$, $N-(L+O)/2$. The sum spectra (a) and (b) for the Pl setting are presented in the upper panels and the corresponding figures (c) and (d) for the Bk setting in the lower panels. They are presented with a bin size of 4channels.

time distribution of $[t_+(E)-t_-(E)]$ would take a rectangular profile very similar to that of $t_-(E)$ distribution. The calculated width wider than that observed ones (cf. Table I) is not understood at the moment. It is worth noting that the time-of-flight spectra of the 762.2-keV conversion electron line and of the 330.3-keV Compton electron line are defined by the electron baffle of 1.0% resolution. Their width was calculated by substituting $\phi_r = 10.0^\circ$ into Eq.(5) and found 38 and 44channels, respectively, which can be compared with the experimental width of 36 and 44channels (cf. Fig. 3(e) and Fig. 5). The agreement between the calculated and experimental values is satisfactory for both cases. The spectral profile more like Gaussian than rectangular might result from the shape of a large aperture made according to the iso-aberration contour. The defining aperture angle varies along the periphery of the aperture while that of the positron baffle for the correlated electrons is constant.

3. *Intensity of peak*

The puzzling phenomenon that the peak appeared not only in M but also in N was explained by the following common fact. The main term of the radial aberration of the present spectrometer is $-4\rho\phi_r^2/3$ of the radial coordinate measured from the optical circle. It corresponds approximately to the full width of the peak and its half could be assumed as the peak position. It implies that the location of a peak taken by a magnetic spectrometer depends on the resolution setting and the better the resolution, the closer it moves to the optical circle due to the decreasing radial aberration. In the present case we set the magnetic field by mistake with the use of the calibration curve made of the 1.0% resolution lines as usually used in the previous experiments. As we discussed in IV A the relevant beam takes ϕ_r =6.2° and $\Delta p/p$=0.5% instead of ϕ_r=10.0° and $\Delta p/p$=1.0% of the usual case. The relative shift of the present peak relative to the usual one was calculated to be 9.5mm to the optical circle side, that is, to the N side. It means that the present peak shifts to the higher energy side by $\Delta p/p = -0.32\%$ because 15mm corresponds to 0.5% (II A).

We determined the displacement μ which produces theexperimental M /N intensity ratio with the condition that the resolution is 0.5% and the momentum distribution is Gaussian. We obtained the displacement μ of -11.4mm, that is, $\Delta p/p = -0.38\%$. This figure fairly well agrees with the value calculated above and the beam shifts is the expected direction. With this Gaussian distribution we can estimate the intensity of electrons arriving in the interval (IT) between the adjacent M and N paddles. The obtained intensity ratios are M/ IT/N=1/2.06/0.62. The total intensity of the relevant electrons was deduced with these intensity ratios and found 740 events.

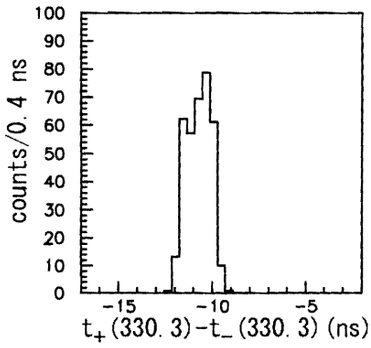

FIG. 8: Monte Carlo simulated M peak. It was produced with 5.1×10^5 trial shots. The center channel, the width and the intensity are determined and compared with the corresponding experimentally observed ones. The spectrum is presented with a bin size of 4channels.

B. Monte Carlo simulations

The experimental results were examined by comparing them with the results obtained by the Monte Carlo simulations. The computation was executed by taking into account the experimental configuration, the multiple scattering in the target and the 180° correlation property of equal energy lepton pairs. The computed spectrum of the M paddle with 5.1×10^5 trial shots is presented in Fig. 8. It reproduces quite well the experimental rectangular like shape. This special spectral profile common to both of experimental and computed peaks would imply that the experimentally observed phenomena could be produced by the physical process adopted for the computation. The difference of time-of-flight, $(t_+ - t_-)$, the width (FWHM) and the intensity are determined −106channels, 20channels and 352counts, respectively. Substituting −106channels into Eq.(2) we obtained P(330.3)=1011channels. The computed location and the width agree satisfactorily with the experimental ones (cf. Table I) With this intensity and the beam resolution of 0.5% we can deduce the total paired electrons arriving on the focal plane by taking into account the spilled electrons in the interval between the paddles. The intensity ratio of the spilled electrons to those on the M paddle was statistically evaluated and found to be 0.45. The total number was determined to be 510events. Dividing the figure by the trial number we can estimate the acceptance probability to be 1.0×10^{-3}. This small figure is provably resulting from the correlation loss caused by the multiple scatterings in the target. The total number of particles produced in the target during the measuring period was calculated by the same prescription as in the previous papers [5–7] and found to be 6.60×10^5[1± 0.13 (stat)± 0.40(syst)]. The large systematic error results from the uncertainties of the estimation of the solid angle of the primary positrons to the target and the effective target thickness and from the errors involved in the cross section reported in the previous paper [4]. The expected yield was deduced by multiplying the total number of the produced particles by the acceptance probability and obtained to be 660[1± 0.13 (stat)± 0.40(syst)]. This yield agrees satisfactorily with 740events obtained in the preceding subsection. The good agreement of the experimental intensity with that derived by using the cross section obtained in the previous singles experiments gives confidence in the assumption that the peaks observed in the singles and coincidence experiments could be the same origin.

V. CONCLUSIONS

The present experimental results are concordant with the scenario that equal-energy 180° correlated positron and electron pairs are emitted simultaneously from a thorium target irradiated by beta decay positrons. We surveyed carefully alternative scenarios that could produce the observed phenomena. All such attempts have failed in explaining the peak with such a narrow width mainly appearing in the spectrum of the M center counter. For instance a 330.3-keV electron produced by a 511-keV annihilation gamma ray via the 8.7° Compton scattering could provide a coincidence pulse with the 180° correlated backward emitted partner annihilation gamma ray. However the energy of the Compton electron changes largely with the emitting angle and in the present case the momentum spread of the electrons passing though the aperture of the baffle is wider than $\Delta p/p$=6%. The electron beam with this momentum spread covers all the paddle counters set on the focal plane.

The suggested scenario meets well the QED requirements for the identification of a neutral object. However unfortunately we could not put forward the particle production mechanism. The present phenomena are so inconceivable in the framework of present-day physics that a new physics would be required to explain them. A confirmation by independent experiments and other groups would be highly desirable.

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