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M. Sakai, M. Imamura, T. Komatsubara, J. Lu,

J. Mukai, T. Shizuma, K. Furuno, T. Hayakawa,

K. Furutaka, M. Kidera, M. Ohshima,

T. Miura and S. Shimizu

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CORRELATED EQUAL-ENERGY TWO - PHOTON EMISSION FROM $e^+(^{82}Sr)+Th$ INTERACTIONS

M.Sakai[1)], M.Imamura[1),*], T.Komatsubara[2)], J.Lu[2)], J. Mukai[2),#], T.Shizuma [2)], K.Furuno[2)], T.Hayakawa[3)], K.Furutaka[3)], M.Kidera[3),+], M.Ohshima[3)], T.Miura[4)] and S.Shimizu[5)]

[1)]Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188,Japan
[2)]Tandem Accelerator Center,University of Tsukuba, Tsukuba, Ibaraki 305 , Japan
[3)]Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-11, Japan
[4)]High Energy Accelerator research Organization, Tsukuba 305, Japan
[5)] Department of Physics, Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan

Abstract

The 330.3±0.4 -keV electron line previously observed at INS in e^++Th interactions has been supposed as the electron product of the e^+e^-decay of an unknown neutral object X^0. If it be the case, QED predicts two-photon decay mode and accordingly the existence of a correlated two-photon coincidence peak. In this case, the energy of the photon and the electron peak must satisfy the relation of $E_\gamma = E_{e^-}+m_ec^2$. Then, the predicted photon energy is given 841.3±0.4 keV. To verify the interpretation, we carried out $\gamma\gamma$ coincidence experiments. Obtained spectra were searched for spectral structures by one-line χ^2 best fit. It revealed a spectral structure of which the energy and the cross section are 841.7±0.3 keV and 10.6±3.1(stat)±6.8(syst)μb, respectively. The upper limit of the cross section was determined 15.2 μb at statistical 95% confidence limits.

A strange experimental result was reported by a group at the Oak Ridge National Laboratory (ORNL)[1)] in 1986. They bombarded a thin Th target with positrons from a ^{68}Ge source and performed coincidence experiments of positrons and electrons emitted from the behind of the bombarded target. They observed a spectral structure at about 340 keV in coincidence spectra. As the coincidence peak indicates that monoenergitic electrons and positrons with the same energy are emitted simultaneously from the irradiated target, they speculated that the phenomenon might result from the e^+e^- decay of an unknown neutral object X^0 generated in positron and heavy atom scatterings. Similar kind of object has been proposed at that time as the origin of the narrow e^+e^- sum lines observed in supercritical heavy ion collisions at Gesellschaft für Schwerionenforschung, Darmstadt m.b.h. (GSI)[2,3)]. As the phenomenon is mysterious and inexplicable in the frame of the present physics, the confirmation of their results was highly expected.

In order to search for the relevant monoenergitic electron beam, we carried out three times by using an iron-free β–ray spectrometer at the Institute for Nuclear Study, University of Tokyo (INS) [4-6)]. We used a rolled Th foil with few mg/cm^2 thickness instead of a 40~50mg/cm^2 target used in the ORNL experiments and positron emitters of ^{118}Te(E_{max}=2.70MeV)[4,5)] and ^{82}Sr(E_{max}=3.37MeV)[6)]. The target placed on a positron emitter was set at the source position of the spectrometer. We observed in each experiment a narrow electron line. The weighted mean energy and cross section were found to be 330.3±0.4keV and 149(1±0.13±0.25)mb[7)], respectively. Small experimental errors indicate a good reproducibility and an internal consistency among the experimental series. We studied the identity of the INS and the ORNL phenomena by using the obtained cross section. The genuine events for the ORNL experiments were calculated with the experimental specifications and the cross section . It was found to be 350 which will be compared with the reported number of events of 500±200.[1]) Furthermore, the observed energy agrees within the experimental error with the ORNL peak. The consistency in respect of the cross section and the energy between the ORNL and INS results may suggest that the two groups observed the same phenomenon though the partner positron beam was not measured in the latter experiments.

The experimental results of the ORNL and INS experiments are not enough to convince the physics community of the validity, because they are not quite compelling due to relatively low statistics and the phenomenon is unbelievable from the theoretical point of view. Moreover, two papers published immediately after the ORNL paper by the Frankfurt and the Argonne group[8,9]) which denied the verity of that research casted doubt on this phenomena. However, we found that both negative results cannot deny the ORNL peak because their conclusions were based on a wrong assumption that the number of genuine events is proportional to the back ground. However, the back ground produced in lepton scattering experiments depends very sensitively on the experimental arrangement. We must calculate the genuine events quantitatively by using the experimental specification, i. e, target thickness, spectrometer transmission, measuring time etc.. The Frankfurt paper did no give experimental parameters enough to calculate the genuine events. On the other hand, the number of genuine events calculated with the Argonne experimental specifications was found to be 30% of that obtained at ORNL due to a small transmission of the used electron and positron spectrometers. The number is far below the experimental sensitivity for the detection of the peak. Therefore, neither ref.8 nor ref.9 could not claim the ORNL peak to be an artifact. Some people suspected the ORNL peak to be originated from the 340keV Compton edge of the 511keV annihilation photon. We measured the Compton electrons scattered out by annihilation photons from the source-target assembly and found a

stepwise platform momentum distribution starting at about 340keV[4]). Consequently, the origin of Compton electrons is highly improbable.

If a neutral object X^0 does exist, QED predicts that it decays by emitting 180^o correlated equal-energy photon pairs in place of e^+e^- pairs as an alternative decay mode. In this case, the photon energy E_γ should satisfy the relation of $E_\gamma = E_{e^-}+m_ec^2$. The predicted value is given 841.3±0.4 keV because of E_{e^-}=330.3±0.4 keV. If X^0 is a spinless and pseudo scalar particle and couples to the photons indirectly via electrons and other charged particles, the branching ratio R of $\sigma(2\gamma)/\sigma(e^+e^-)$ would be given by the following formula[10]):

$$R=\sigma(2\gamma)/\sigma(e^+e^-)\geq(\alpha/\pi)^2(M/m_e)^2\,(1-4m_e{}^2/M^2)^{-1/2}, \qquad 1)$$

where M stands for the mass of X^0 and the inequality represents the possibility of coupling to other charged particles beside the electron. In the case of E_{e^-}=330 keV, R calculated is $\geq 7.4\times10^{-5}$. Then, $\sigma(2\gamma)$ is given $\geq 11(1\pm0.13\pm0.25)\mu b$ by introducing the reported $\sigma(e^+e^-)$ into eq.1. The observation of a coincidence peak with the predicted energy will present a strong support for the proposed nature of the electron line and provide an evidence of X^0. Also, the determination of R imposes a crucial constraint for X^0 models because it depends sensitively on the properties of coupling of X^0 to other charged particles.

Motivated by the argument described above, we have carried out five independent $\gamma\gamma$ coincidence experiments from 1994 to 1997. The experimental series are denoted as I, II, III, IV and V. Three or five Ge detector pairs were installed in a dodecahedral framework and aligned back to back. Detectors with relative efficiencies of 40~50 % were surrounded by BGO anti-Compton shields. Absorbers of 5.0 mm lead and 0.5 mm tin plates were placed in front of each detector. Also, each detector was provided with a 3 cm long hollow conical lead plug that insured an effective 9^o half-angle opening into the Ge detector. Each detector was equipped with a pile-up rejector to reduce the back ground. As positron emitters we used ^{82}Sr sources of about 3.7MBq. A chemically separated ^{82}Sr was deposited on a mylar membrane or absorbed in a thin 4mm ϕ resin membrane. It was shielded by sandwiching in both sides with 12mm ϕ mylar disks of 100μm thick. The source target assembly was prepared by placing the shield source between 6mm ϕ rolled thorium plates of 1.35 g/cm^2 in thickness. This disk like assembly was put at the center of the detector system.

All coincidences between any two detectors were recorded event by event, where pulses were selected by setting discrimination levels at about 520 keV to reduce 511-511 coincidences. First, a two-dimensional (E_1E_2) event map was made by sorting the data. The matrix element of the map, $N(E_1,E_2)$, consists of events registered in a 0.5keVx0.5keV bin. Then, we summed the elements satisfying the condition of $|E_1-E_2|\leq$ 2, 4 and 6 keV along the direction perpendicular to the diagonal line, that is, $E_1+E_2=2E_0$ and constructed the coincidence spectra in a function of E_0. The procedure means that we make the spectra with the events recorded in the gate of 2, 4 and 6 keV width centered at E_0 on the diagonal line because the searched events should locate there. The summing under the condition of $E_1+E_2=2E_0$ is suited for the present experiments because it can correct the Doppler broadening which could occur in case the photons are emitted from a moving object. The spectra thus obtained were added together for all the experimental series. Sum spectra are presented in Fig.1- A, -B and -C corresponding to the gate width of 2, 4 and 6 keV, respectively. We notice a spectral structure at around 841.5 keV. The energy agrees fairly well with the predicted value. A large bump observed in the region around 850 keV results from the coincidence of pulses produced by pile up of the 511-keV annihilation photon and the Compton photon. The peak at 881.6 keV was accounted for the coincidences of the 2^+-0^+ transition and the Compton tails of the cascade gamma rays in ^{84}Kr, of which the parent activity of ^{84}Rb is a contaminant found in the sources of III and IV

experiments. The line shape of the observed peak and the nuclear gamma peak resembles each other. It may imply that the former peak could be the photon origin like the latter. To study the spectral nature of the peak, we examined separately the spectrum obtained in each experimental series.The spectra gated with 4 keV width are presented in Fig.2 together with the sum spectrum. Due to the low statistics, the each spectrum does not show any noticeable peak structures. However, some excess counts around 841-keV region appear in all the spectra and, by adding spectra, that part of the spectrum develops into a visible peak while the other peak structures are fading out. Such evolution of the peak with increasing statistics might suggest the peak to be of physical origin.

The peak intensity was estimated by constructing a simulated background with use of the widely accepted event-mixing procedure. First, we made a simulated background map by computing each element of 0.5keVx0.5keV bin, $B(E_1E_2)$, with use of the following formula:

$$B(E_1E_2) = \frac{\sum_{E_j} N(E_1E_j) \times \sum_{E_i} N(E_iE_2)}{\sum_{E_iE_j} N(E_iE_j)} \qquad 2)$$

The computation was executed in the square region of E_1(780-1000keV)xE_2(780-1000keV). Second, using the newly constructed $B(E_1E_2)$ map, we made a simulated background spectrum with the same sorting conditions as in the case of coincidence spectra. The sum of the simulated spectra for each experiment is shown as a smooth curve in Fig.1-A,-B and -C.

The intensity, $N_{2\gamma}$, of a spectral structure at around 841.5keV were roughly estimated with the counts obtained by subtracting the simulated spectra from the coincidence spectra. It was found 20.7, 32.6 and 27.6 counts for the case A, B and C, respectively. The intensity increases from the case A to the case B, but does not increase from the case B to the case C. It shows that the gate setting of 4 keV is enough to take all the genuine events. Therefore, we will adopt the result of B for the following statistical analyses. First, one-line χ^2 best fit was carried out in a spectrum range between 821 keV and 860 keV(40 one-keV bin) by using of the CERN Lib. MINUIT. The result is shown in Fig.3. It revealed a spectral structure, of which the energy and the intensity are 841.7±0.3keV and 34.2±10.0, respectively, with χ^2=50.7. A fairly large χ^2 value is due to a negative excursion at around 844keV. As the negative value is not physical, we took it as the systematic error and adopted the intensity of 34.2±10.0(stat)±22.0(syst). The errors are considerable so that this figure may be taken marginal for discussing of a peak structure. Therefore, we thought it wise to determine the upper limit of peak intensity by using the statistical argument of ref.11. It was given 49 at statistical 95% confidence limits (2 times the standard deviation) for a 4-keV-wide photon line.

The production cross section, $\sigma(2\gamma)$, was deduced with the same assumptions as those used in the previous papers[4-6]. Namely, X^0 is produced with a constant cross section by the positrons above the threshold energy, E_{th}, where we define $E_{th}=2E_\gamma$ and photons are emitted isotropically. In the present case we employed the following convenient and reliable method. We observed a prominent coincidence peak of the 697-keV-698-keV nuclear cascade γ rays of ^{82}Sr in the diagonal cut spectra due to their almost equal energies. $N_{2\gamma}$ and $N_{\gamma\gamma}$, the intensity of the cascade γ peak, are proportional to the source intensity, the count reduction factor of the pile-up rejector and the gate width. Therefore, if we take the ratio R of $N_{2\gamma}$ to $N_{\gamma\gamma}$, these quantities common in the numerator and the denominator are canceled out. Then, the ratio R is written as a following simple formula :

$$\frac{N_{2\gamma}(841)}{N_{\gamma-\gamma}(697-698)} = \frac{[m\eta l] \times 10^{-3} \div 232 \times 6.0 \times 10^{23} \times \sigma}{b(1+\Delta)W(\theta)\Omega} \cdot \frac{\epsilon^2(841)}{\epsilon^2(697-698)} \qquad 3)$$

The meaning of the symbols in eq.3 is following:

ε^2: square of the effective detector efficiency for pair detectors. It includes the photon absorption in the target and in the absorber and the crystal efficiency. We obtained $\varepsilon^2(841)=3.45\times10^{-2}$ and $\varepsilon^2(697\text{-}698)=3.76\times10^{-2}$, respectively.

b: branching ratio of the relevant cascade decay chain. The figure of 4.4 x 10^{-4} was taken from ref.12.

Δ: correction of $N_{\gamma\gamma}$ for the contribution of coincidence events produced by the Compton tail of the strong 776-keV transition in ^{82}Sr and the cascade gamma rays.

$W(\theta)$: angular correlation function of the cascade gamma rays. It was obtained by using the nuclear properties of the relevant transitions in the Table of Isotopes[13] and given as $W(\theta)=1+0.213P_2(\cos\theta)+0.326P_4(\cos\theta)$. Then, W(180)=1.5.

Ω: solid angle of the detector. It was 6.16×10^{-3}.

$m\eta l$: effective target mass for production in unit of mg/cm^2.

m: target thickness in mg/cm^2.

η: fraction of positron spectrum above E_{th}.

l: positron effective path length in unit of m.

In case of a thin target as used in electron measurements, we can calculate $m\eta l$ to a good approximation by treating each quantity separately. However, in the case of a bulk target as in the present experiments, these quantities interweave each other, so that we employed the following procedure. Primary positrons with energy of E_{e+} continue to produce X^0 along a flight path l until they lose the energy of $E_{e+}-E_{th}$. The flight path was calculated by range-energy table. Then, we integrated l numerically in a function of positron energy and emission angle by taking into account the effect of energetic positrons passing through the target and the momentum distribution of the positron spectrum. We also considered the edge effect that the positrons emitted from the periphery of the source does not fully interact with the target. We obtained $m\eta l$=247mg/cm^2. The calculated value could contain certain errors because we ignored the effects of straggling and back scattering of positrons in the target. Introducing these numerical values into eq.3, we found $\sigma(\mu b)=0.73\times10^4R$. Being $N_{\gamma\gamma}$=23300±150 counts, we obtained $\sigma(2\gamma)=0.31\times N_{2\gamma}\,\mu b$. By using this conversion formula, we deduced the cross section of 10.6±3.1±6.8 μb and 15.2 μb ≥for the case of one-line χ^2 best fit and of statistical 95% confidence limits, respectively. These values can be compared with the lower bound of $\sigma(2\gamma) \geq 11(1\pm0.13\pm0.25)\mu b$ obtained by eq.1.

The ensemble of the experimental information from the experiments of positron and heavy ions scatterings [1,4-6,14] yield certain image of the physical nature of X^0. The width of both of the electron line[4-6] and the coincidence gamma line[14] are limited by the instrumental resolution to the extent that the intrinsic width can not be deduced. The upper bound of the intrinsic width is estimated less than 1.5keV, which corresponds to the life time greater than 4.3×10^{-19}sec. It indicates the object to be formed at rest. The fact is against the postulation of the object as the resonance state of the Bhabha scatterings, because in this case the width of the peak should broaden due to Doppler effect. It might explain the unsuccessful results of all the Bhabha scattering experiments so far performed. Consequently, the incident positrons might not be the constituent of the object and the phenomenon could be produced by three body process. Taking into account all these facts, we are lead to an image of X^0. Incident positrons with a small impact parameter approach near the nucleus by slowing down due to the repulsive force and produce the object in the strong nuclear Coulomb field in cooperation with an unknown interaction and leave the nucleus. In other words, the positrons excite the ground state of a nuclear system consisted of a nucleus and a X^0 by giving it an energy of 841x2 keV like incident protons in inelastic reactions. The participation of the strong Coulomb field in the X^0 production manifests the following experimental fact that the cross section depends strongly on the atomic number of the target. We measured the cross section with Th and U targets[2] and found the ratio of $\sigma(U)/\sigma(Th)=1.2$. If we assume $\sigma\propto Z^x$, x is deduced to be about 9. It explains the fact

that the line could not be observed with a Ta target[2] because the calculated cross section for the Ta target is 24mb which is far below the instrumental sensitivity for line detection. It is strongly desirable to establish the Z dependence by determining the cross section with other targets like Pt, Pb etc.. The dependence could give us an important insight into the mechanism of the formation of X^0. Finally, to verify the scenario, we propose a positron inelastic experiment, i.e., bombarding monoenrgitic positrons on the heavy element and analyzing the momentum of scattered positrons. A satellite peak could be expected to appear at an energy by 1684 keV(841keVx2) lower than that of the elastic peak.

The present experimental results satisfied the conditions of $E_\gamma = E_{e^-}+m_ec^2$ and R $\approx\alpha^2$ which are required by the scenario of the formation of X^0. If the existence of X^0 had been theoretically predicted, the present results would be easily accepted as the confirmation of the scenario and the evidence of X^0. However, we are not such a situation. Many theoretical attempts have not succeeded in constructing a theory which can formulate X^0. 2γ experiments of heavy ion collisions performed at Berkeley[15-17] did not find the coincidence peaks corresponding to the e^+e^- GSI lines. Moreover, recent e^+e^- experiments of heavy ion collisions[18-20] failed to observe the GSI lines. Consequently, though positron and heavy atom scatterings and heavy ion collisions are completely different from each other in physical nature, we must present a compelling evidence for convincing of the credibility of the phenomenon in question. In this sense, the present results with statistical level of 3σ and a large systematic error must be considered to be marginal for proving the existence of X^0 and only to impose an upper limit with statistical confidence limits for the production cross section. To pin down this issue, further investigations must be carried out by increasing the number of detector pairs to produce spectra with much higher statistics.

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*Present address : National Museum of Japanese History, 117 Jonai-cho, Sakura, Chiba 285, Japan

#Present address : Towa University ,Chikushigaoka, Fukuoka 815, Japan

+Present address : Institute for Physical and Chemical Research, Wako, Saitama 351-01, Japan

Figure Caption

Fig.1 Coincidence spectra. A, B and C correspond to those taken with the gate of $|E_1-E_2|\leq$ 2, 4 and 6 keV, respectively. Smooth curves are simulated background spectra (see text).

Fig.2 Spectrum of each experimental series and the sum spectrum. They were taken with the gate width of 4keV.

Fig.3 Goodness of fit resulting from the χ^2 test. Full black points are observed counts.The dashed line is the best fitted one. The dot-dashed line is the contribution of Gaussian line determined by the best fit procedure.

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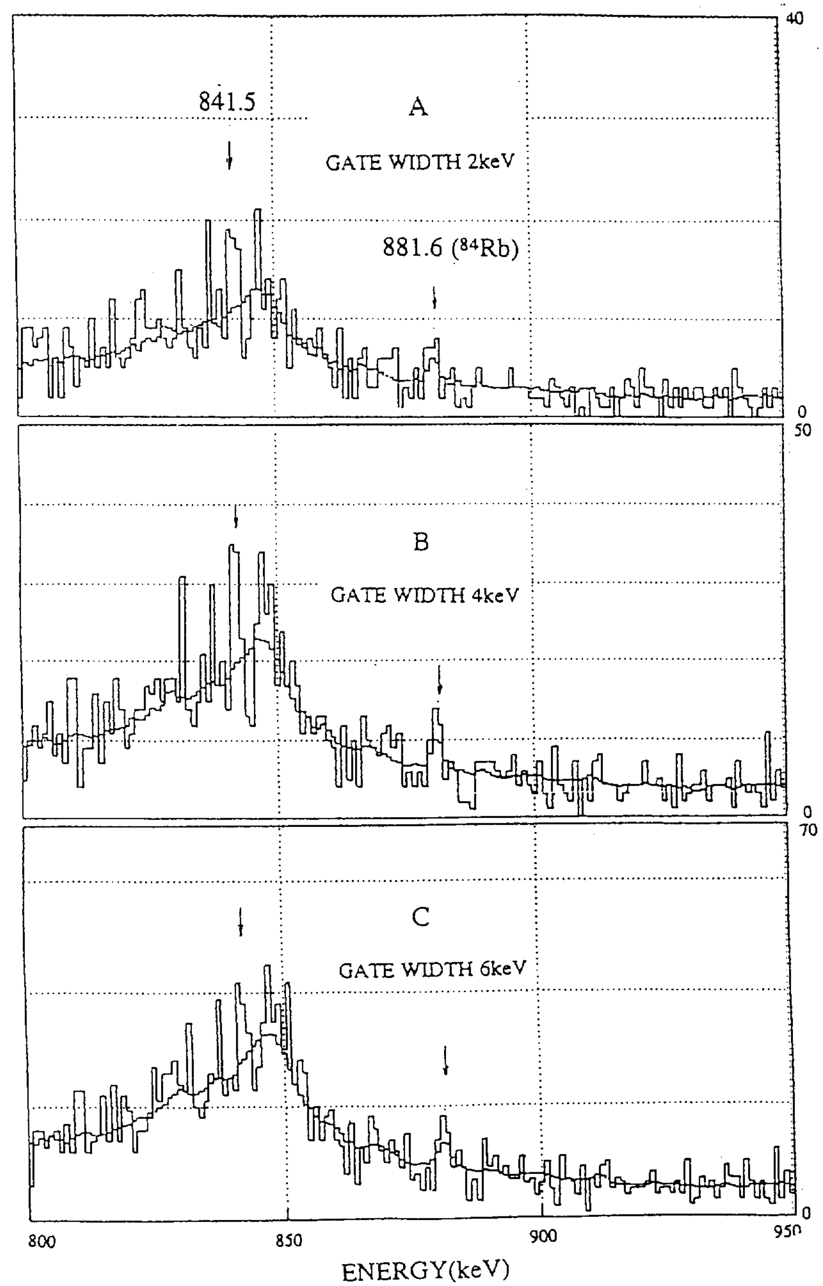

Fig.1

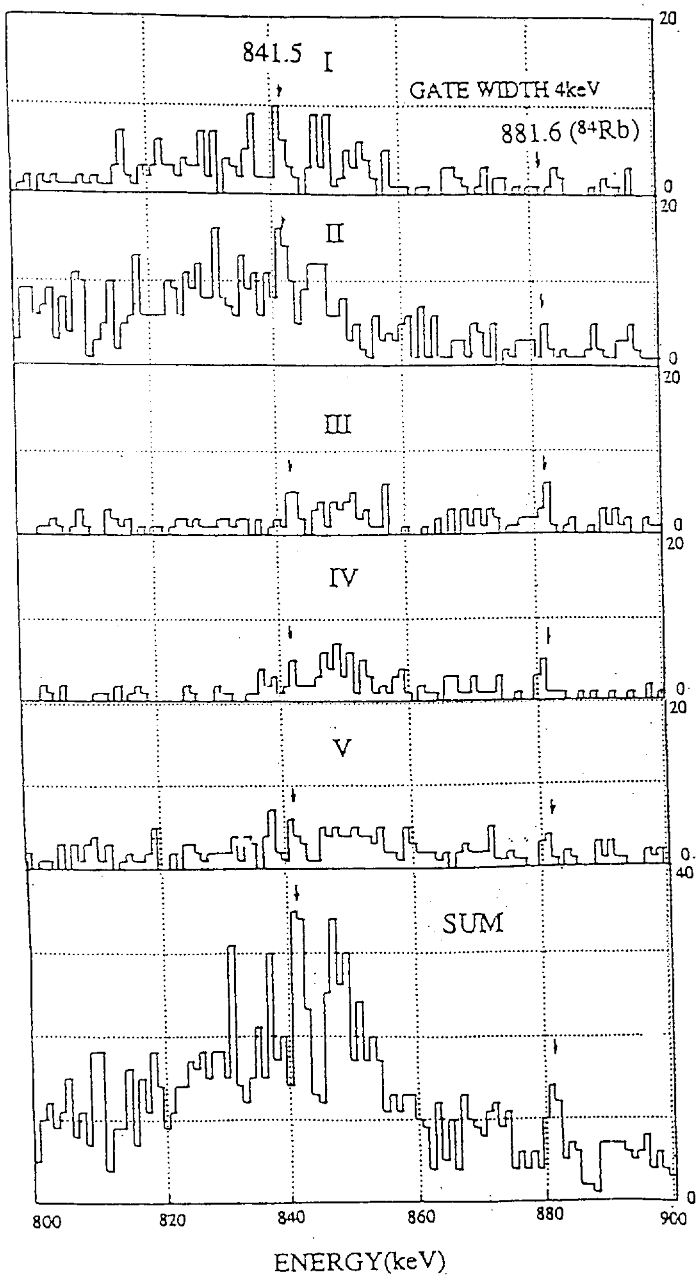
841.5
I
GATE WIDTH 4keV
881.6 (^{84}Rb)
II
III
IV
V
SUM
800
820
840
860
880
900
ENERGY(keV)

Fig.2

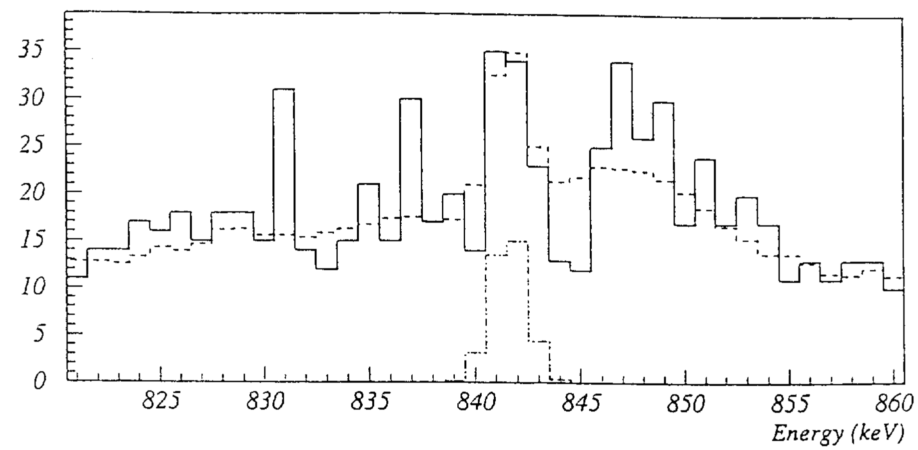
35
30
25
20
15
10
5
0
825
830
835
840
845
850
855
860
Energy (keV)

Fig.3