Title	ニュートリノの出ない二重ベータ崩壊および関連した話題の実験的研究
Author(s)	上窪田, 紀彦
Citation	大阪大学, 1986, 博士論文
Version Type	VoR
URL	https://hdl.handle.net/11094/1483
rights	
Note	

Experimental Studies for Neutrino-less Double Beta Decays and Related Topics

Norihiko Kamikubota

DISSERTATION IN PHYSICS

THE OSAKA UNIVERSITY

GRADUATE SCHOOL OF SCIENCE

TOYONAKA, OSAKA

Experimental Studies for Neutrino-less Double Beta Decays and Related Topics

Norihiko Kamikubota

Dept. Physics, Osaka University

Abstract

Neutrino-less double beta decays ($0\nu\beta\beta$) of ^{76}Ge have been studied by means of an ultra-low background system ELEGANTS (ELEctron GAmma NeuTrino Spectrometer). The $0\nu\beta\beta$ process is lepton number non-conserving process due to the finite Majorana neutrino mass (m_ν) and/or the non-vanishing right-handed coupling (V+A) term in weak interaction. The purpose of this work is to search for the possible m_ν and V+A terms by means of a precise β-γ spectroscopic study of the $0\nu\beta\beta$ decays of ^{76}Ge $0^+\to0^+$ and $0^+\to2^+$ transitions. Since the double beta decay is the second order process of the weak interaction, it is extremely rare phenomenon with a halflife of $10^{20}\sim10^{24}$ years. The $0\nu\beta\beta$ process in the 2n mechanism is the process where the emitted neutrino from one nucleon is re-absorbed by another nucleon in the same nucleus. Therefore the transition rate of the $0\nu\beta\beta$ process in the nucleus is much enhanced compared with that of the usual $2\nu\beta\beta$ process because of the short frying distance of the virtual neutrino. Thus the nucleus is considered to provide a good micro laboratory for the $0\nu\beta\beta$ experiment.

The ELEGANTS has been developed and has been constructed for the ultra-low background β-γ study of the $0\nu\beta\beta$ process. It consists of a high resolution Ge β-detector surrounded by a 4π-NaI γ-counter. There are two characterustic points of the ELEGANTS. One is the use of a 4π-NaI counter to measure all γ-rays accompanied by β-ray and electron signals from the Ge detector. Another is the list mode data taking which means that all the signals from the detectors are stored event by event and recorded in a magnetic tape. The construction and the performance of the ELEGANTS are described in detail. The precise spectroscopic study of both the β- and γ- rays is shown to be very powerful not only to select the 0νββ decay events from a large amount of backgrounds, but also to investigate the origin of backgrounds in the Ge spectra. The sensitivities of the ELEGANTS for detecting the 0νββ processes of ^{76}Ge are found to be one of the best ones among the other types of detectors used by other groups.

The measurements have been made at the Kamioka underground laboratory for totally 8577 hours. No appreciable peak beyond backgrounds were observed. Lower limits on the halflives are obtained as 7.4×10^{22} years for the $0^+\to0^+$ transition and 5.6×10^{22} years for the $0^+\to2^+$ transition, respectively, both on the 68 % confidence level. The former limit is as good as the other experiments, while the latter gives quite stringent limit on the $0^+\to2^+$ process. The limits on the neutrino mass and the right-handed coupling term are evaluated from the present data to be 3.6 eV and 0.4×10^{-5}, respectively, by using a calculated matrix element. While they are 5.6 eV and 0.6×10^{-5} by using another calculation. On the other hand use of the matrix element guessed from the observed 2νββ value in the other nucleus leads to larger limits by a factor of 2.4. Note that all the limits above are based on the presnt halflife data on the 68 % confidence level.

The present result on the neutrino mass is consistent with the other 0νββ counter experiments. On the other hand the finite neutrino mass of 36±4 eV was reported from the tritium β-decay experiments. It is difficult to give definite conclusions on the neutrino mass at present, since one must consider the types of

neutrinos obtained by expeiments and experimentql errors as well as ambiguities in theoretical calculations. These problems on the neutrino mass together with the possible contribution of m_ν to the astrophysical constraints on the mass of the Universe are still open. These problems will be worked out by future improved experiments.

The ELEGANTS is also applicable to search for weak radioactivities as well as for the $0\nu\beta\beta$ decays of the other $\beta\beta$ sources. It is shown that an activity of $\sim 10^{-15}$ Curie can be detected by one week measurement of the ELEGANTS. It is far beyond the standard levels of this field.

CONTENTS

CHAPTER 1 Introduction

1-1 Introduction to the double beta decays

The double beta decay is the transition from a nucleus of Z to Z±2. It is observable if the first order process $Z \rightarrow Z\pm1$ is forbidden from the Q value or almost forbidden because of the large difference of spin and parity. In fact the possible candidates are found in many even-even nuclei with the 0^+ ground states. Those are listed in Table 1-1. The energy schemes for two typical double beta decay triplets, ^{76}Ge decays into ^{76}Se and ^{48}Ca decays into ^{48}Ti, are shown in Fig. 1-1.

There are two possible channels for the double beta decay. The normal double beta decay ($2\nu\beta\beta$) emits two electrons and two neutrinos. Then the lepton number is conserved. While the neutrino-less double beta decay($0\nu\beta\beta$) emits two electrons only. Then it does not conserve the lepton number. They are written as follows.

$$(2\nu\beta\beta)\ A_Z \rightarrow A_{Z+2} + e^- + e^- + \overline{\nu} + \overline{\nu} \qquad (1\text{-}1\ a)$$

$$(0\nu\beta\beta)\ A_Z \rightarrow A_{Z+2} + e^- + e^- \qquad (1\text{-}1\ b)$$

Both processes are expected to occur as the result of a second-order effect.

The problem of double beta decays has been discussed for over 50 years. In fact the halflife of the $2\nu\beta\beta$ process was first calculated by Mayer in 1935 (Mayer35), based on the first presentation of weak interaction by Fermi in 1933 (Fermi34). The $2\nu\beta\beta$ process is expected from the standard theory. The recent study of this process has the significance that the $2\nu\beta\beta$ matrix element may be used to evaluate the nuclear matrix element for the $0\nu\beta\beta$ process. The $0\nu\beta\beta$ process is of current interest in view of the possible lepton number non-conservation. The first suggestion to this process was made by Furry in 1939 (Furry39). The interest at that time was that the 0νββ was regarded as a possible means of determining whether the neutrinos are the Dirac or Majorana particles. It is still correct that both 0ν and 2ν process are possible by the Majorana description, while the Dirac theory allows only the 2νββ process. The theoretical and experimental reviews on the status of these old period were presented in references (Primakoff59, Antonio60). After the discovery of parity non-conservation in 1957, the theoretical situation had changed much. The 0νββ process was forbidden even with the Majorana description, since the virtual neutrino emitted in the intermediate step had the wrong helicity to produce the subsequent inverse beta decay. Actually the 0νββ process can be possible only for the case that the virtually emitted neutrinos do not polarized purely, but have a small mixing of different helicity. It requires the finite neutrino mass and/or the right-handed coupling (V+A) term in weak interaction (Doi81, Doi83a, Doi83b, Primakoff81, Kotani84a). Therefore the 0νββ decay is regarded as a very powerful prove for studying the neutrino mass and the right-handed coupling.

1-2 The theoretical aspects for the 0νββ decays

1-2-1 Mechanisms of the 0νββ process

The 0νββ process is interpreted as follows, a neutrino emitted from one nucleon is re-absorbed by another nucleon in the same nucleus, as is shown in Fig. 1-2(a). The distance of two nucleons is much shorter than the wavelength of the neutrino emitted outside the nuclei in the normal $2\nu\beta\beta$ decay. Thus the $0\nu\beta\beta$ process is much enhanced over the $2\nu\beta\beta$ process by a factor of $(\lambda\!\!\!^{-}/R)^6 \sim 10^8$. This is called 2n-mechanism. (n means 'nucleon')

Since the Δ isobar has an isospin 3/2, the $0\nu\beta\beta$ process can be possible by one step Δ process as

$$\Delta^- \rightarrow p + e^- + e^- \qquad (1\text{-}3\ a)$$

$$n \rightarrow \Delta^{++} + e^- + e^- \qquad (1\text{-}3\ b)$$

They are called N^*-mechanism. The processes are shown in Fig. 1-2(b) and (c). The one step Δ process is a kind of a two step quark mechanism in analogy to the above mentioned 2n-mechanism, namely, a neutrino emitted from one quark is re-absorbed by another quark in the same nucleon. Therefore the mechanism is enhanced over the 2n-mechanism by a factor of $\sim$ 30, which is the square of the ratio between the nucleon distance and the quark distance. Furthermore the overlap integral for the Δ process is large. Consequently the Δ process (N^*-mechanism) can be as large as the 2n-mechanism, even though the probability of the Δ in a nucleus is of the order of a few percent.

Doi, Kotani, Nishiura and Takasugi studied the angular momentum and parity conservations of emitted electrons and neutrinos for the nuclear transitions (Doi83a). They proved that the Δ process did not contribute to the $0^+\rightarrow 0^+$ transition because of the 2/3 spin of the Δ isobar. The selection rule for both the $0\nu\beta\beta$ and the $2\nu\beta\beta$ modes are given in Table 1-2. It is noted that if the $0^+\rightarrow 2^+$ transition in the 0ν mode is observed, it means that the existence of the right-handed current in addition to the Majorana character of neutrinos. Then the observation of the $0\nu\beta\beta$ for both the $0^+\rightarrow 0^+$ and $0^+\rightarrow 2^+$ transitions makes it possible to determine the neutrino mass term and the right-handed coupling term individually.

Possibilities of other mechanisms have also been studied. For example the Majoron emission mechanism (George81, Gelmini81), the Higgs boson exchange mechanism (Mahapatra81, Wolfenstein81, Rizzo82, Schechter82) have been reported by several authors. In this report, however, they are not discussed. It should be noted that the energy and angular distributions of the two β-rays depend on the terms contributing to the 0νββ process, (Doi83c). Therefore β-γ spectroscopic studies of the 0νββ $0^+ \to 0^+$ and $0^+ \to 2^+$ transitions may provide the constraints on the 0νββ mechanisms.

1-2-2 Formulations for the 0νββ decays

The theoretical estimate for the 0νββ decays have been made by several groups under the framework of the gauge theory with the left- and right-handed interactions (Primakoff69, Primakoff81, Doi81, Doi83a-c, Doi84, Kotani84a-b, Haxton81, Haxton84). Here we use formulae and notations developed by Doi, Kotani and Takasugi et. al.. The general charged current weak interaction is expressed as

$$H_W = \frac{G}{\sqrt{2}}\left[j_{L\rho}^{\dagger}\cdot(J_L{}^{\rho} + \kappa\cdot J_R{}^{\rho}) + j_{R\rho}^{\dagger}\cdot(\eta\cdot J_L{}^{\rho} + \lambda\cdot J_R{}^{\rho}) \right] + hc.,(1\text{-}5)$$

where $j_R(J_R)$, $j_L(J_R)$ are right-handed and left-handed leptonic (hadronic) currents, respectively. The first term is the weak interaction in the standard minimal electroweak model of $SU(2)_L \times U(1)$, while others are the right-handed V+A interaction terms. Coupling constants (κ, η and λ) are the ratios of right-handed mixings. They are related with each other (Kotani84a).

Here let's introduce the three parameters corresponding to m_ν, η and λ.

$$x \equiv |\sum_j m_j \cdot U_{ej}{}^2| / m_e = \langle m_\nu \rangle / m_e \tag{1-6 a}$$

$$y \equiv \lambda \cdot |\sum_j U_{ej} \cdot V_{ej}| \cdot |g'_V / g_V| \tag{1-6 b}$$

$$z \equiv \eta \cdot |\sum_j U_{ej} \cdot V_{ej}| \tag{1-6 c}$$

The weak eigenstate neutrinos ($\nu_{\ell L}$ and $\nu'_{\ell R}$) are assumed to be the superposition of the mass eigenstate neutrinos (N_{jL} and N_{jR}). U and V in Eq. 1-6 represent the mixing matrices. The coupling constant κ in Eq. 1-5 is expected to be smaller than unity and appears always as $(1 \pm \kappa)$. Thus one may negrect its contribution.

The halflife for the $0^+ \to 0^+$ transition in the $0\nu\beta\beta$ mode is expressed as (Doi84)

$$\left[T_{0\nu}(0^+ \to 0^+)\right]^{-1} = \log_e 2 \cdot F(x,y,z) \cdot |M_{GT}^{0\nu}|^2 \tag{1-7 a}$$

$$F(x,y,z) = c_1 x^2 + c_2 xy \cdot \cos(\psi + \alpha) + c_3 xz \cdot \cos\psi$$
$$+ c_4 y^2 + c_5 z^2 + c_6 yz \cdot \cos\alpha \tag{1-7 b}$$

$$\psi = \arg[\sum_j (m_j / m_e) \cdot U_{ej}{}^2 \times (\sum_j U_{ej} \cdot V_{ej})] \tag{1-7 c}$$

$$\alpha = \arg(g'_V / g_V) \tag{1-7 d}$$

The GT-type nuclear matrix element $M_{GT}^{0\nu}$ is major since the Fermi-type $M_F^{0\nu}$ is mostly exhausted by the isobaric analogue state. The coefficients c_i in Eq. (1-7) include the nuclear and kinematical terms and the ratio of $M_F^{0\nu}/M_{GT}^{0\nu}$.

The 0ν $\beta\beta$ process for the $0^+ \to 2^+$ transition is due to the right-handed terms. It has the Δ isobar contribution as well as the 2n one. The transition probability is written as (Doi84)

$$\left[T_{0\nu}(0^+ \to 2^+)\right]^{-1} = \log_e 2 \cdot [D_1 y^2 + D_2 yz \cdot \cos\alpha + D_3 z^2] \tag{1-8 a}$$

$$D_1 = D_1' + D^*,\ D_2 = D_2' - 2D^*,\ D_3 = D_3' + D^*,\ D^* = G_{N^*}|X_\Delta|^2 \quad (1\text{-}8\ b)$$

where the D_i''s include the nuclear and kinematical terms and the nuclear matrix elements for the 2n-mechanism, while the D^* is for the Δ isobar process.

The forms and numerical values for the kinematical and nuclear terms and the nuclear matrix elements have been discussed in detail by several groups (Doi84, Haxton81, Haxton84, Zamick82, Klapdor84, Grotz83). As for the nuclear matrix elements for the $0\nu\beta\beta$ $(0^+ \to 2^+)$ process, all of the values have been hardly evaluated until now, because there are several matrix elements contributing to this process.

1-3 The experimental researches for the $0\nu\beta\beta$ decays

1-3-1 The experimental methods to detect the $0\nu\beta\beta$ decays

From the experimental views, the $0\nu\beta\beta$ process has a very attractive property. Since it emits two electrons only, they should share the total transition energy. Therefore in the spectrum of the sum energy of electrons it gives a sharp peak at the $\beta\beta$ transition energy. However, the $0\nu\beta\beta$ decay is an extremely rare process, and the problem of backgrounds is very serious.

There are two types of experiments. One is the geochemical method, and another is the direct (counter) experiment. The geochemical method measures the amount of daughter nuclei (A_{Z+2} in Eq. 1-1) in the old ore by means of the mass spectroscopic technique. The excess of the nuclei over the abundance in the atomosphere is considered to be due to the $\beta\beta$ process. This method has a benefit that the measurement period corresponds to the age of the ore, which is usually $\sim 10^9$ years. Kirsten summarized the $\beta\beta$ geochemical measurements and showed the world average of the halflives, which were orders of $10^{20\sim21}$ years for the decay of ^{130}Te, ^{82}Se etc. (Kirsten83, Kirsten84a-b). These results are quoted in Table 1-3. However, there are some disadvantages such as the ambiguity of the age determination, the possibility of the escape of the daughter nuclei during the geochemical period, and the possibility that the daughter has been produced by other processes, etc.. Moreover this method can not distinguish the $0\nu\beta\beta$ process from the $2\nu\beta\beta$ process.

The direct observation of two electrons in coincidence is free from the disadvantages seen in the geochemical method. In the following sections we review the direct counter experiments performed so far.

1-3-2 The techniques for direct counter experiments

Following techniques are characteristic to the $\beta\beta$ decay experiments and valuable to pick up the true events.

(1) The basic idea is to make a coincidence measurement for two electrons. For example, the situation that a thin $\beta\beta$ source put between two counters face to face each other and are operated in coincidence provides a considerable reduction of backgrounds. The anticoincidence with surrounding detectors as compton suppressor and for cosmic-ray veto is also useful.

(2) One of the other ways to eliminate backgrounds is achieved with the visual observation of electron tracks. It is possible with the cloud chamber, the drift chamber, and the nuclear emulsion. When an appropriate magnetic field is applied, one can identify the

electrons from the curvature of tracks. The simultaneous measurement of energies and directions for detected electrons is more preferable.

(3) To prepare two sources, one contains the ββ nuclei and another contains the isotope with different A. It is important to measure both specimens and discuss the difference between them. This is because one can not exclude the possibility that the observed candidate for the ββ decay may be an accidental background event. It is recommended that the 'true' sample and the 'dummy' are measured alternately for relatively short period, since the performance of the detector system may change gradually for a long period of measurements.

(4) To use a special detector which contains the ββ source inside the detector itself. This method is expected to have fairly good sensitivity to detect the ββ events. The advantages of this technique are (a) a 4π-geometry for a source without self absorption, and (b) the energy resolution and the efficiency are independent of the relative angular and energy distribution of the two electrons. The possible cases are the CaF_2 scintillation detector for ^{48}Ca, the Xe gas (or liquid) chamber for ^{136}Xe, and the Ge detector for ^{76}Ge. The implantation of the ββ source into the detector is also expected to improve the result.

1-3-3 Review of the direct experiments

It is not the present purpose to make a complete review of the ββ experiments. Detailed review before 1960 are available in the references (Antonio60, Primakoff59). Review of the recent experimental status are given in other references (Haxton84, Fiorini84, Bellotti84).

1-3-4 Experiments for the $0\nu\beta\beta$ decay of ^{76}Ge

Recent years many measurements to search for the $0\nu\beta\beta$ decays have been made. This is because the $0\nu\beta\beta$ decay has been regarded as one of the powerful ways to test the non-zero neutrino mass, which was reported in 1980 by Lubimov (Lubimov80). Especially recent works have been concentrated on the possible decay of ^{76}Ge. Followings are the characteristic points on the measurement of ^{76}Ge.

(1) Natural Ge contains 7.76 % ^{76}Ge which can decay to the ground state of ^{76}Se ($0^+ \to 0^+$ transition) with a transition energy $Q_{\beta\beta}$ = 2040.71±0.52 keV (Ellis84). An alternative decay of interest is the $0^+ \to 2^+$ transition, The ^{76}Ge may decay to the first excited state of ^{76}Se at 559.1 keV with a transition energy $Q_{\beta\beta}$ = 1481.6±0.5 keV.

(2) The $0\nu\beta\beta$ decay would be revealed by the presence of peaks corresponding to the $0^+ \to 0^+$ and $0^+ \to 2$ transition energies. Since the peaks should be found in the continuum background spectrum, an excellent energy resolution ($\sim 10^{-4}$) is very attractive.

(3) The Ge detector works as both a detector of 100 % efficiency and a source with zero thickness. Since total detector volume is smaller than other experiments, the amount of backgrounds is smaller.

The use of the Ge detector was first suggested in 1967 and a series of experiments had been carried out from 1967 to 1973 by the Milano group (Fiorini72a-b, Fiorini73). The measurement was made.for 4400 hours in the laboratory situated in Mont Blanc tunnel (4200 m.w.e.). The layers of heavy shields were placed around the Ge detector, which were mercury, copper, low-activity lead, normal lead, and paraffine from the inside to outside. The result of halflife limits were 5×10^{21} years for the $0\nu\beta\beta$ $0^+\to0^+$ transition, and 2×10^{21} years for the $0\nu\beta\beta$ $0^+\to2^+$ transition, both at 68% confidence level (C.L.).

The experiments of the $0\nu\beta\beta$ decay of ^{76}Ge have been made in 1980's by several groups. We do not intend to present detailed descriptions for all groups, but show the summary table in Table 1-4, which shows the experimental results of the $0\nu\beta\beta$ decay of ^{76}Ge as well as experimental parameters. Reported halflife limits at present are an order of 10^{23} years for $0^+\to0^+$ transition, and 10^{22} years for the $0^+\to2^+$ transition. Among those groups the Milano and the PNL/USC groups give the best limit of $\sim12\times10^{22}$ years for the $0^+\to0^+$ decay, while for the $0^+\to2^+$ decay the best limit is 5.6×10^{22} years reported by our group in this thesis.

1-3-5 Future directions of the $0\nu\beta\beta$ decay of ^{76}Ge

Plans for future experiments of ^{76}Ge have two tendencies. One is to operate at an underground laboratory. Some groups make (made) a collaboration with the proton decay experimental groups in order to realize an underground experiment in near future. Another is to use the Ge detectors with totally $\sim$1000 cc volume. The plans of every group are given in Table 1-5. Some of them (PNL/USC, USCB/LBL) are already realized in part, and are expected to get considerably better results within next $2\sim3$ years. The Osaka group does not have a future plan on the experiment of ^{76}Ge, but have plans with other $\beta\beta$ sources. (See Chapter 4-2)

CHAPTER 2 An Ultra Low Background System 'ELEGANTS'

2-1 Introduction

There are strong demands from various fields on high-resolution low-background detectors for β- and γ-rays. They are used to detect and/or identify extremely weak β- and/or γ-rays associated with very important rare events. Actually there are many important rare decays which are crucial for nuclear and particle physics. Great attention has recently been focussed on the possible rare events of neutrino-less double beta decays (0νββ). The 0νββ event rate, however, is considered to be less than one per 10^{22} years, while background rate of natural radioactivities for a standard bare detector is an order of $10^9 \sim 10^{10}$ per year. Therefore the detector for the rare 0νββ event has to be well shielded against backgrounds and has a capability to select (identify) the true event among huge background events. Such detectors with low-background and high-selectivity can be used not only for pure science but also for development of low radioactive materials, tracing low radioactivities and so on.

Specifications required for such detectors are high energy-resolution, high efficiency, low-background and high selectivity. High energy-resolution leads to high selectivity. It is important to emphasize high selectivity of true events among other background events, since detectors can not be absolutely free from backgrounds.

The purpose of this chapter is to report details of our high-selectivity low-background detector for β- and γ-rays and its performance. This is primarily developed to search for the 0νββ decay of ^{76}Ge. The Ge detector is used as the β-ray detector as well as the ^{76}Ge source since natural Ge used for the detector contains

7.76 % of the ^{76}Ge.

The present detector comprises β(electron)- and γ-detectors to search for 0νββ events associated with a finite neutrino mass and the right-handed weak interaction. Thus it is called ELEGANTS (ELEctron GAmma-ray NeuTrino Spectrometer). It consists of a high-resolution large-volume Ge detector surrounded by NaI(Tl) detectors with a 4π-geometry and plastic scintillators. These detectors are shielded from natural radioactivities by low-activity metallic shields. The main point of the ELEGANTS is the use of 4π-NaI(Tl) counter in coincidence with the Ge detector. This is essential for high selectivity because the true β event is accompanied by the particular (or no) γ-ray(s), while most of natural radioactivities are accompanied by many γ-rays characteristic of the decay schemes. Thus γ-ray signals are used as references to identify the true β event among huge background events. The essential part of our detector and the result have been briefly presented in the conference (symposium) proceedings, (Ejiri84a, Ejiri85a-b) and the most recent 0νββ result is given in the reference. (Ejiri85) In the followings the design principles for low-background system are given in Chapter 2-2, and details of the specifications of the ELEGANTS are written in Chapter 2-3. Measured data are presented in Chapter 2-4, and the analyses of the origins of the backgrounds are in Chapter 2-5.

2-2 Principle for high-selectivity low-background system

2-2-1 High resolution semiconductor detector

High energy-resolution is necessary for high selectivity of a true discrete line among other discrete and continuum backgrounds. Discrete lines are mainly due to γ-rays from natural radioactive isotopes, while continuum components are due to Compton scatterings, β-rays and cosmic-rays. Semiconductor detectors, being used in low temperature, have merits of high energy-resolution with high stability and low-background because of the small volume purified crystal.

A particular point of the Ge detector for the 0νββ process is that the natural Ge contains 7.76 % ^{76}Ge ββ source nuclei. Thus the Ge detector serves as both a detector of 100% efficiency and a ββ source of zero thickness, as already mentioned in Chapter 1-3-4.

2-2-2 Origins of backgrounds

It is crucial for the detection of very rare (weak) events to discriminate true signals from other background signals. The way depends on origins of the background (Knoll79). In order to know the origins, many measurements have been made first at the sea-level laboratory of the Osaka University for convenience, and at the 1000 m (2700 m water equivalent) underground laboratory of the Kamioka mine to get free from cosmic-rays. The background consists of many discrete lines and continuum components. There are two origins for the backgrounds. One is due to natural radioactivities (RI) associated with ^{232}Th and ^{238}U chain products and ^{40}K. Another is due to cosmic-rays (CR). As a matter of fact the CR is reduced much at the underground laboratory.

These backgrounds are classified into five groups.

(1) RIE : γ-rays from natural radioactive isotopes outside the Ge detector. Some are room backgrounds and others may come from shields themselves which are used to protect the detector from the room

background. They are called external backgrounds.

(2) RII : β- and γ-rays from natural radioactive isotopes contained in materials used for the Ge detector. They are called internal backgrounds.

(3) RIA : β- and γ-rays from decay products of ^{222}Rn in the air around the detector.

(4) CRC : Charged cosmic-rays such as μ-ons and electrons.

(5) CRN : Neutral cosmic-rays such as neutrons induced by cosmic μ-ons etc. They give rise to γ-rays by (n,n'γ) and (n,γ) reactions on materials used for the detector.

In fact the RIE is the major background source for a bare detector and all others manifest themselves only after reducing the RIE by means of heavy shields.

2-2-3 Selection of true signals and rejection of backgrounds

Following devices are used for selecting true signals and rejecting backgrounds.

(1) External shields

High-Z heavy metals are effective for shielding γ-rays. Lead bricks are used most conveniently. However, even pure lead contains some amount of radioactivities, γ-rays from which have to be reduced much in order to achieve an ultra low-background detector system. Oxygen free high conductive copper (OFHC), which contains little radioactivities, can be used inside the lead shield to reduce the γ-rays from the lead bricks. Mercury is easily purified to a level of five nines, and is effective to reduce low-energy γ-rays and X-rays. Thus it is used inside the OFHC bricks.

These metallic shields with effective thickness of a range of

$35 \sim 50$ cm reduce external γ-ray background (RIE) down to an order of $10^{-8} \sim 10^{-10}$. This reduction rate is sufficient. It, however, is not effective for backgrounds of other origins, which become very important after reduction of the RIE.

(2) Low radioactive materials

Internal backgrounds (RII) can be reduced to some extent by selecting low-activity materials. OFHC, Ti, and Mg metals, which are processed carefully, are found to have radioactivities less than a couple of 10^{-15} Curie/gram. This is almost a limit of the RI measured by a specially designed low-background counter, namely a test model for the ELEGANTS. It consists of a 60 cc Ge detector placed in a center hole of a 7"φ×6" NaI. They are shielded by 10 cm thick lead bricks. Radioactivities in materials used for the Ge detector itself and other parts of the ELEGANTS were checked by using this model. Actually the upper limit of about a couple of 10^{-15} Curie/gram is not sufficient for detecting $0\nu\beta\beta$ events. It is noted that recently extremely low-background Ge counters for $0\nu\beta\beta$ decay have been constructed by using specially selected materials. (Liguori83, Brodzinski85, Jagem85)

(3) γ-detectors

The internal RI (RII) can be discriminated from the true $0\nu\beta\beta$ event by measuring efficiently all γ-rays associated with the RII. Most of the RI contained in the materials used for the counters are U and Th chain isotopes. They emit a number of γ-rays. One of them makes Compton scattering inside a Ge crystal, giving a continuum background underlying the $0\nu\beta\beta$ discrete line. Therefore the background event is followed by the Compton scattered γ-ray and other γ-rays characteristic of the decay. The $0\nu\beta\beta$ true event feeding the ground state is followed by no γ-ray and the event feeding the first 2^+ excited state is followed by the particular $2^+ \to 0^+$ γ-ray. Thus an efficient observation of all the γ-rays in coincidence with the β signals from the Ge detector is very powerful to identify the origin and to select the true event.

Here a γ-counter consisting of multi-detectors is convenient to measure the γ-ray multiplicity. High γ-multiplicity (n) of the RII helps a lot. Lets take an example of γ_1, γ_2 and γ_3 cascade decay from ^{208}Tl, as shown in Fig. 2-1. Here Compton scattering of the γ_3 in the Ge detector contributes to the electron background at around $E_e \simeq 1.5 \sim 2$ MeV. Then probability of missing all γ_1, γ_2 and the Compton scattered γ_3' is an order of $(1-\varepsilon)^3$ where ε is the γ-ray detection probability. Thus 4π γ-counter with $\varepsilon \simeq 0.9$ gives $\varepsilon)^3 \simeq 10^{-3}$. Here the materials used for the Ge counter (cold finger, housing, cap etc.) have to be low-Z light elements in order to avoid an absorption of the γ-rays.

(4) Air ventilation

The background (RIA) due to Radon gas around the detector can be reduced by putting the detector in an air-tight box and/or by ventilating the air around the detector. The major RIA is γ-rays from ^{214}Bi, which is a decay product of ^{222}Rn. Because the halflife of Radon is 3.8 days, Radon gas activities around the detector kept in an air-tight box decay away in a couple of weeks. The Radon content depends much on the ore in the underground laboratory.

(5) Active shields

An active shield made of plastic scintillators is used to detect charged cosmic-rays (CRC). Slow μ-ons which stop near the detector after passing through the active shield (plastics) give rise to electrons by μ-decays or neutrons and γ-rays by μ-capture reactions. The decay life is an order of a few μ-sec. Thus the time window for the anticoincidence with pulses from active shield counters has to be about a few ten's of μ-sec. to catch the decay products. Note that the 4π-NaI γ-counter surrounding the Ge detector can serve as a good active shield as well as the γ-counter.

(6) List mode data taking

It is important to record in a list mode all energy and timing signals from the β-counter(Ge), all the NaI detectors comprising the 4π γ-counters and the active filters (plastic scintillators). They are analyzed offline to select the true events and to check energy calibration. Some of histograms are displayed by the online analysis to monitor the counters. In view of a long run over years to search for extremely rare events, checking all counters and electronics by the list mode data taking is indispensable.

(7) Underground laboratory

Neutral particles (neutrons) are hardly rejected by external (active or not active) shields unless cosmic-rays responsible for them are cut away. Energy of cosmic-rays extend far beyond GeV. Thus one of most efficient way to avoid such cosmic-rays are to set the detector at a deep underground laboratory.

2-3 Specifications of the high-resolution high-selectivity detector system 'ELEGANTS'

Details of the ELEGANTS are shown in Fig. 2-2. It is composed by a Ge detector for ββ-rays, a 4π-NaI detector for γ-rays, external shields and plastic scintillators. The Ge detector is made of coaxial-type 171 cc pure Ge with the energy resolution of 1.8 keV for 1.33 MeV ^{60}Co γ-rays. The fiducial volume as the $\beta\beta$ source is 164 cc. Materials used for the detector are such light elements as Magnesium, teptzel etc.. Radioactivities have been checked to be not more than $(1\sim2)\times10^{-15}$ Curie/gram. From these points of view the Ge cap is made of Magnesium alloy instead of usual Alminium. On the basis of background tests and selections of the materials the Ge detector was designed in collaboration with ORTEC, and was manufactured by ORTEC.

The γ-detector is composed by a well type 10"ϕx12" NaI crystal and an 8"ϕx3" NaI crystal. The well-type crystal is segmented into five pieces. These six pieces of the NaI crystals altogether comprises a 4π-geometry detector for high-multiplicity γ-rays. The energy resolutions of six NaI segments are $9\sim10$ % for 0.661 MeV ^{137}Cs γ-rays. Light reflectors used are MgO powder and teflon sheet. The OFHC was used for the casing and quartz was used for the window. The low-background type photo-multipliers were used. All these materials have been checked for the radioactivity. The measured radioactive contaminations are given in Table 2-1.

The efficiency of the γ-detector array was measured by using radioactive isotopes, and was checked by a Monte Carlo calculation. They agree well with each other. As an example lets consider a radioactive isotope with 4-multiplicity γ-rays. Three of them are 550 keV and one of them is Compton scattered in the Ge detector with energy of 550 keV. The probability of missing all four γ-rays in the γ-detector is as small as $10^{-3} \sim 10^{-2}$.

The passive shields consist of 2.7 cm mercury with 99.999 % purity, 15 cm OFHC and 15 cm lead for low-background measurements. These metallic shields, together with the NaI crystals, reduce external background γ-rays in the 1.5 ∿ 2.5 MeV region by factors $10^{-9} \sim 10^{-10}$. The OFHC, together with the NaI crystal, reduce satisfactory even γ-rays from lead absorber. Unfortunately the mercury contains a small amount of the ^{194}Hg isotope with halflife of 260 years. It emits 1885.9, 1887.0, 1924.0 and 2043.7 keV γ-rays, the last one being close to the 2040.7 keV for the 0νββ of the ^{76}Ge $(0^+ \rightarrow 0^+)$. Therefore the mercury shield has been removed at the underground laboratory. [Appendix A] At sea-level Osaka, the 0.5 mm thick Cadmium sheet and 1 m thick paraffine blocks are mounted on the top of the ELEGANTS as a shield against neutrons. It should be noted that neutrons can be produced by cosmic-rays at any place inside as well as outside the ELEGANTS, and can pass through the active filters, namely plastic and NaI detectors.

Plastic detectors with a thickness of 1.5 cm and a 3/4π solid angle were inserted between the OFHC and lead shield. They give 2 ∿ 4 MeV pulses for most of charged μ-ons penetrating the ELEGANTS. Neutrons and γ-rays following μ-capture reactions in the metallic shields contribute to the background of the Ge detector. Thus all pulses from the Ge detector which follow pulses from the plastic detectors within 10 μ-sec. are rejected. Cosmic neutrons comming from outside the ELEGANTS may produce γ-rays by inelastic or capture reactions. Compton scattering of these γ-rays in the Ge detector gives background signals. They are distinguished by detecting Compton scattered γ-rays with the NaI γ-counter. It should be noted that the 4π-NaI detector serves as a very good detector for charged cosmic-rays.

In order to avoid all kinds of backgrounds due to cosmic-ray the whole system has been set at the Kamioka underground laboratory in the Kamioka mine at about 1000 m (2700 m water equivalent) depth. Cosmic μ-ons are reduced by a factor of 3×10^5 in the underground laboratory. Indeed the large continuum background exceeding beyond 3 MeV disappeared as shown in Fig. 2-3. Thus the plastic counters and the neutron shield (Cadmium and paraffine) are not used in the underground laboratory.

Intensity of background γ-rays of ^{214}Bi, which is the decay product of ^{222}Rn, increases by a factor 14 in the Kamioka underground laboratory covered by granite rocks. Thus air space inside the OFHC shield is filled by lucite bricks to decrease the Radon gas content. Furthermore the air around the Ge detector was blown away by introducing N_2 gas evaporated from the liquid N_2 coolant of the Ge detector as shown in Fig. 2-2. By this method the ^{214}Bi background level decreased down to the same level as the sea-level laboratory. (See Chapter 2-4 and Fig. 2-8)

Energy and timing signals from detectors are fed into the PDP11/10 computer through CAMAC. All signals are recorded by event by event list mode in a magnetic tape. Event was triggered by signals from the Ge detector. The event rate is typically 1.3 per sec. at the sea-level laboratory of Osaka Univ., and 0.06 per sec. at the Kamioka underground laboratory. The electronics and the data taking by a mini-computer for the ELEGANTS are given in Appendix C. The time and the date of the every event are recorded as well, and are used to check any effect on the detector system due to unexpected conditions inside and outside the detector. At the Kamioka underground laboratory, we sometimes happen to meet unexpected power-line shut down. The recorded data on a magnetic tape can be saved even in such accident. The energy calibration and the resolution check were made for data in every run by referring to the discrete lines from background activities such as 352 kev, 609 kev, 1461 kev, 2615 kev and so on. The energy resolution is typically 2.5 keV and 3.0 keV at the 1.5 and 2.0 MeV region, respectively.

2-4 Performance

2-4-1 Energy spectra

Energy spectra of the Ge detector at the sea-level laboratory of Osaka Univ. and at the Kamioka underground laboratory are shown in Fig. 2-4 and Fig. 2-5, respectively. The singles spectra obtained with the bare Ge detector are shown as the mode B. Mode S, A and C stand, respectively, for the singles, the anticoincidence with all signals from NaI γ-detectors and plastic detectors, and the coincidence with the 559 keV $2^+ \rightarrow 0^+$ transition in ^{76}Se. The mode G is the singles spectrum obtained by introducing the N_2 gas around the Ge detector at the underground laboratory. The mode A is to select the $0\nu\beta\beta$ decay of ^{76}Ge to the 0^+ ground state in ^{76}Se, being accompanied by no γ-rays. While the C is to select the $0\nu\beta\beta$ decay of ^{76}Ge to the first excited 2^+ state in ^{76}Se, being followed by the $2^+ \rightarrow 0^+$ γ-ray. A broad peak around the energy of 900 keV is seen in the spectra of the mode C. This is due to the Compton scattering of 1461 keV γ-ray from ^{40}K. Counting rates of typical discrete γ-rays and continuum components at the sea-level of Osaka Univ. are listed in Table 2-2(a). Those at the Kamioka underground labo. are in Table 2-2(b).

For the measurement at the sea-level Osaka, the background rates at the $Q_{\beta\beta}(0^+\rightarrow 0^+) \simeq 2041$ keV and the $Q_{\beta\beta}(0^+\rightarrow 2^+) \simeq 1482$ keV are 1.8×10^{-3} and 7.6×10^{-4} per keV per hour, respectively. The non-intelligent (external) shields reduced the background rates for the $0^+\rightarrow 0^+$ and $0^+\rightarrow 2^+$ cases by factors 28 and 35, respectively. While the intelligent (event-selective) mode reduced them by additional factors of about 150 and 320, respectively. These reduction rates do indicate important contribution of internal radioactivities around the detector. For the measurement at Kamioka, observed background rates at energies of $Q_{\beta\beta}(0^+\rightarrow 0^+)$ and $Q_{\beta\beta}(0^+\rightarrow 2^+)$ are 6×10^{-4} and $(2\sim3)\times10^{-4}$ per keV per hour, respectively.

Yields of γ-rays due to ^{222}Rn are indeed larger at the underground laboratory (mode B and S) than those at the sea-level laboratory. They come down to the same level as the sea-level laboratory by introducing the N_2 gas (mode G). The reduction rate by requiring the anticoincidence (mode A) depends much on the γ-ray multiplicity and the location of the activity. The ^{40}K gives only one 1.461 MeV γ-ray. Therefore the peak yield is not reduced in the mode A. On the other hand yields of γ-rays from U and Th chain isotopes with high γ-ray multiplicities, as well as are yields at the continuum region due to the scattering and cosmic rays, are indeed much reduced in the anticoincidence mode.

2-4-2 Sensitivity of the detector for the 0νββ of ^{76}Ge

Lower bounds of halflives (upper bounds for transition rates) measured by the ELEGANTS can be obtained from a condition that the number of true events exceeds fluctuation of the background events. Let's introduce here a sensitivity $S_i(1/2)$ of the detector system. It is defined as

$$S_i(1/2) = N_0 \cdot k_i / \sqrt{N_i(BG) \cdot \Delta E} \qquad (2\text{-}1)$$

where N_0 is the number of ^{76}Ge source nuclei in the fiducial volume, k_i is the detection efficiency, $N_i(BG)$ is the background rate per year per keV, and ΔE is the energy resolution in keV. The suffix 'i' shows the mode for transitions, i = 0 for the $0^+ \rightarrow 0^+$ and i=1 for the $0^+ \rightarrow 2^+$ transition. Then the limit of the halflife measured for a running time of t year is estimated to be roughly

$$T_{1/2} \lesssim 0.53 \cdot S_i(1/2)\sqrt{t} \qquad (2\text{-}2)$$

where the coefficient 0.53 is a product of $\log_e 2$ and the probability 0.76 for the true event falling in the energy window of ΔE.

The detection efficiency k_i depends on the transition energy and on the γ-rays associated with the transition. In case of the $0\nu\beta\beta$ of ^{76}Ge to the ground state in ^{76}Se, the γ-rays are detected in the anticoincidence with any of six NaI segments since there are no γ-rays accompanied. While the $0\nu\beta\beta$ decays to the first 2^+ excited state in ^{76}Se are measured in coincidence with the 559 keV $2^+ \rightarrow 0^+$ γ-ray in one of six NaI segments. Thus the detection efficiency k_0 for the 0^+ final state is $k_0 = 1$, while k_1 for the first 2^+ final state is given by $k_1 = (1-\beta)\alpha$ where α is the total peak efficiency of the NaI detector for the $2^+ \rightarrow 0^+$ γ-ray and β is the absorption coefficient of the γ-ray in the Ge detector. The β was evaluated to be $\beta \simeq 0.56$ by the Monte Carlo calculation. The α for 559 keV $2^+ \rightarrow 0^+$ γ-ray is 0.64 ± 0.04. Then k_1 was obtained as $k_1 = 0.28 \pm 0.02$. Actually the energy window for gating the 559 keV γ-ray is about 100 keV. Correcting for the contribution of the multicompton events falling in the energy window, the overall efficiency is $k_1 = 0.34$.

The sensitivities of the ELEGANTS are listed together with those of other groups in Table 2-3(a) and (b). The sensitivities for the $0^+ \to 0^+$ $0\nu\beta\beta$ of ^{76}Ge at the Kamioka underground laboratory is as good as the most recent ones (Bellotti84b, Avignon84, Caldwell85) and are better than others. The sensitivity of the ELEGANTS for the $0^+ \to 2^+$ $0\nu\beta\beta$ of ^{76}Ge exceeds much all others.

2-5 Origins of the backgrounds

2-5-1 Cosmic-rays observed at the sea-level laboratory

Since the external shield reduces the RIE (external RI background) by factors $10^{-9} \sim 10^{-10}$, the remaining backgrounds are mainly due to cosmic-rays and internal RI's (RII). The contribution from the CRC (charged cosmic-ray) at the sea-level laboratory is evaluated as follows.

The active shield of the plastic counter spans such a solid angle that rejects effectively about 2/3 of the CRC, while the 4π-NaI γ-counter does almost 100 %. Since it consists of the six NaI segments, one gets a multiplicity distribution f(M) defined as the fraction of events of the Ge counter accompanied by the multiplicity M signals (number of the NaI segments fired) from the NaI counters. Then the multiplicity distributions observed at the sea-level with and without the active (plastic) shield are obtained as $F_A(M) = \frac{2}{3} f_C(M)$, and $F_N(M) = \frac{1}{3} f_C(M) + f_R(M)$, respectively. Here $f_C(M)$ and $f_R(M)$ denote the distributions for the CRC and the other sources, respectively. The $f_C(M)$ and $f_R(M)$ are obtained from the observed $F_A(M)$ and $F_N(M)$ as shown in Fig. 2-6. The $f_C(M)$ spreads over a region of $M = 2 \sim 6$, while $f_R(M)$ is localized mainly in a region of $M = 0 \sim 2$. This is explained by the CRC penetrating the $2 \sim 3$ segments of NaI and some electron showers. The total CRC $\sum_M f_C(M)$ at the sea-level amounts to about 90 %. Making use of this property, it is possible to reject only the background component due to the CRC effectively by requiring the multiplicity of less than or equal to 2 ($M \leq 2$).

The values $f_C(0)$ and $f_R(0)$ are background events accompanied by no signals from any NaI segments, thus are not rejected by the anticoincidence with the NaI counter. The $f_C(0)$ is only 0.3 %, but $f_R(0)$ is still about 2.6 % at the sea-level. The RII and CRN are considered to be major sources. Actually the background spectrum with the NaI anticoincidence mode (Fig. 2-4(b) mode A) extends beyond 3 MeV and ends at 8 MeV. Here 3 MeV corresponds almost to maximum energies of the γ and β-rays from RI and 8 MeV to γ-rays from neutron capture.

One can find some other evidences for the neutron capture reactions at the sea-level laboratory by searching for the peaks following neutron capture reactions. The spectrum of the Ge at sea-level Osaka shows clear peaks at the energies of 139.7 keV and 198.9 keV, which can not be observed at Kamioka underground. (Fig. 2-7) Forster et. al. reported that these two peaks are due to decays from the isomer of ^{75}Ge and ^{71}Ge, respectively. They may be produced by the neutron capture reaction of ^{74}Ge and ^{70}Ge. (Forster84)

2-5-2 Radioactivities observed at the underground laboratory

Cosmic μ-ons at the Kamioka underground laboratory is reduced more than four orders of magnitudes. Actually the singles event rate above 4 MeV at the sea-level is reduced by factors $10^2 \sim 10^3$ by requiring anticoincidence with the NaI counter, and by factors $10^3 \sim 10^5$ by moving the detector to the underground laboratory. Anticoincidence with the NaI counter does not improve the spectrum much beyond 3 MeV at the underground laboratory. Thus the remaining background extending to 4 ∿ 5 MeV (see Fig. 2-5(b)) is considered to be due to sum of β- and γ-ray signals, and the background at higher energy region may still come from cosmic rays.

Almost all discrete lines prominent below 3 MeV are due to decays of ^{238}U and ^{238}Th chain isotopes. Fig. 2-8 shows normalized intensities $I_n(\gamma)$ for the ^{238}U chain isotopes. Here I_n is expressed as

$$I_n(\gamma) = \frac{I(\gamma)}{\varepsilon(\gamma)\cdot\delta(\gamma)} \qquad (2-3)$$

where $I(\gamma)$ is the observed peak intensity, $\varepsilon(\gamma)$ is the peak efficiency for the Ge detector and $\delta(\gamma)$ is the fraction of the γ intensity per decay. Large excess of the $I_n(\gamma)$ due to ^{222}Rn gas, which is observed in the underground laboratory, disappeared by blowing out the air around the Ge detector. Then the normalized intensities are all constant and are well balanced, indicating no additional ^{214}Bi γ-rays due to Radon gas. Thus they all come from the ^{238}U isotopes located somehow near the Ge detector. This is because the $I_n(\gamma)$'s for low energy γ-rays would be smaller due to absorption if the RI would be in the NaI crystal or in outer OFHC shield. The large reduction of the $I_n(\gamma)$ by the anticoincidence with the NaI is consistent with location of the RI in the internal region.

^{214}Pb with $T_{1/2}$ = 26.8 m is a decay product of ^{238}U. It decays two ways, the β^- decay with $E_\beta(max)$ = 672 keV is followed by a single γ-ray of 351.9 keV and the β^- decay with $E_\beta(max)$ = 729 keV is followed by a single γ-ray of 295.2 keV. The intensities of these γ-rays are reduced by 10 % in the anticoincidence mode with the NaI counter. Thus some fractions (10 %) of these β-rays have to be detected by the NaI counter. Fig. 2-9 shows β-ray energy spectra measured by the NaI counter in coincidence with the 295.2 keV and 351.9 keV γ-rays measured by the Ge detector. These data indicate that at least 20 % of the ^{238}U chain isotopes contributing to the backgrounds are located inside the OFHC case of the NaI crystal since the β-rays from the ^{214}Pb outside the case can not reach the NaI crystal. Similar analysis also indicates that some fractions of the ^{208}Tl activities exist inside the OFHC case of the NaI crystal.

It is noted that we don't observe γ-rays of ^{210}Pb, ^{210}Bi and ^{210}Po, which are the ^{238}U chain isotopes. They are reported to be contained in the lead shield (Jagem85), but are considered to be well reduced by the 15 cm thick OFHC in the present case.

CHAPTER 3 Double Beta Decay of ^{76}Ge with the ELEGANTS

3-1 Activities in Osaka University

The first researches for double beta decays in Osaka University can be found in 1966. N. Takaoka and K. Ogata, who majored in the mass spectroscopy, investigated the abundance of ^{130}Xe in the old ore produced in Ohtani Japan. They assumed that the observed excess of ^{130}Xe in the ore over the natural abundance in the air was the decay product of the double beta process of ^{130}Te. They concluded that the halflife of the double beta decay of ^{130}Te was $(8.20\pm0.68)\times10^{20}$ years. (Takaoka66)

In 1980, M. Doi, T. Kotani, H. Nishiura, K. Okuda and E. Takasugi started to study the theoretical transition probability of double beta decays. The first achievement by them were published in 1981. (Doi81) They calculated the halflife ratio of ^{130}Te and ^{128}Te and compared it with the ratio obtained from geochemical measurements. The conclusion suggested that neutrinos are Majorana particles and have finite mass around 30 eV if they relied on the result of geochemical measurement by Missouri group.

The experimental search for the neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge in Osaka University was first proposed by H. Ejiri in 1981. Many kinds of preliminary measurements were done in 1982 to search for the origin of backgrounds observed in Ge spectra. Another important work in this year was the test for radioactive contaminations contained in detector constructing materials. (See Table 2-1) The result of this test was used to construct the Ge detector in collaboration with ORTEC and the NaI detectors with BICRON. They are the central parts of our detector assembly

'ELEGANTS'. In this chapter the author gives details of the series of experiments to search for the $0\nu\beta\beta$ of ^{76}Ge by Osaka group in recent years.

3-2 The experimental apparatus 'ELEGANTS'

Since the double beta decay is considered to be due to the second order weak process, it is an extremely rare phenomenon. The expected counts of the neutrino-less double beta decay of ^{76}Ge is less than 10 counts per year for the 200 cc Ge. Thus one has to pick up the small events in the huge amount of background counts. An ultra-low background system 'ELEGANTS' (ELEctron GAmma-ray NeuTrino Spectrometer) was constructed to study the neutrinoless double beta decay of ^{76}Ge. The central part of the ELEGANTS consists of a pure Ge detector with 171 cc active and 164 cc fiducial volume and six NaI(Tl) detectors surrounding the Ge with 4π-geometry. More details of the ELEGANTS are given in Chapter 2-3. Among recent $0\nu\beta\beta$ experiments of ^{76}Ge introduced in Chapter 1-3, the experiments with the ELEGANTS have three significant features.

(1) Use NaI γ-ray detectors with 4π-geometry

The use of 4π-NaI detectors is based on the idea to measure all the γ-rays in coincidence with the β-ray signals from the Ge detector. This makes it possible to pick up the $0^+\rightarrow0^+$ and $0^+\rightarrow2^+$ double beta processes of ^{76}Ge efficiently from a large amount of backgrounds. (See also Chapter 2-2-3(3))

(2) Operate at an underground laboratory in relatively earlier time

Apart from the experiment by Milano group (Fiorini73), we were the first group to decide the movement of the apparatus from a sea-level to an underground laboratory. It is the best method to exclude the backgrounds due to cosmic-ray related events, especially due to neutrons. In fact we could realize the considerable improvement on the background reduction. (See Chapter 2-4-1) At the Kamioka underground laboratory the observed counting rate at the energy of 2 MeV, where the peak of the $0\nu\beta\beta$ decay of ^{76}Ge is expected, was 6×10^{-4} counts per keV per hour. It was the lowest one among published reports when we first obtain this improved data. Later other groups also decided (or at least have a plan) to move their apparatus into underground environment.

(3) Record the events in list mode on a magnetic tape

All the signals from the detectors and the arrival time of each event are recorded event by event list mode on a magnetic tape. This enables us to investigate the various correlations between the signals by using proper gate conditions during an offline analysis. It is a powerful tool to investigate the origins of backgrounds. Here shows some results as examples : the discovery of ^{194}Hg in natural mercury [Appendix A] and the detection of β-ray signals from the decay of ^{214}Pb inside the NaI detector. (See Chapter 2-5-2)

3-3 Measurements

3-3-1 Measurements with the ELEGANTS

Measurements with the ELEGANTS for the $0\nu\beta\beta$ decay of ^{76}Ge have been made by Osaka group. The measurements are divided into three groups. The first run (RUN 1) was made for about 2115 hours at the sea-level laboratory of Osaka Univ.. The second run (RUN 2) and the third run (RUN 3) were made at the underground laboratory in the Kamioka mine located about 1000 m (2700 m water equivalent) depth.

The second run was the measurement for 1600 hours. After the RUN 2 was completed, the mercury shield was removed and the RUN 3 started. The RUN 3 has been operated for about 7000 hours up to now (January 1986) and will soon be stopped in order to replace the Ge detector by the stack of Si detectors and ^{100}Mo sources.

3-3-2 RUN 1 at the sea-level Osaka

The first run (RUN 1) was made at the sea-level laboratory of OULNS (Laboratory of Nuclear Studies Osaka Univ.) from December 1983 to May 1984. Every measurement was about 2 $\sim$ 3 days of running time, which was determined by the capacity of a magnetic tape. Some of the measurements were stopped for considerably short period, especially at the beginning. It was because of the bug of the mini-computer software, electronics troubles and other happennings. These short runs were summarized up to at least about 50 hours for the energy calibration and the resolution check. They were done for every data of 30 $\sim$ 80 hours by referring to the γ-ray lines from background activities. The energy resolutions of RUN D19 and D20 were much worse than others. This was considered to be due to the humidity at the experimental room. These data are not used for the analyses of the $0\nu\beta\beta$ decay. The total effective period for the $0\nu\beta\beta$ decay of ^{76}Ge is 2115 hours.

The energy calibrations of the six NaI segments were made between the successive runs by measuring the background activities for 1461 keV from ^{40}K and other peaks during one over-night ($\sim$12 hours). The positron annihiration peak at 511 keV was observed for every run and used also for the NaI energy calibrations.

During the first half of RUN 1 denoted, plastic scintillators did not operate well since the levels of all discriminators were set to be higher than appropriate levels. Fortunately it did not affect the result of the $0\nu\beta\beta$ decay. At the beginning of the next half, paraffin blocks of 1 m thick and Cadmium sheets were mounted on the top of the ELEGANTS in order to decrease the neutron flux. But no apparent improvement was found.

The observed background rates at our interest, namely at the $Q_{\beta\beta}(0^+\to0^+) \simeq 2041$ keV in anticoincidence with surrounding 4π-NaI detectors and the $Q_{\beta\beta}(0^+\to2^+) \simeq 1482$ keV in coincidence with $2^+\to0^+$ 559 keV γ-ray, were found to be 1.8×10^{-3} and 7.6×10^{-4} /keV•hr, respectively.

3-3-3 RUN 2 at the Kamioka underground laboratory

The major source of the background, which could not be rejected by an anticoincidence with surrounding NaI detectors, was analyzed to be due to the neutron capture reactions. Then next run was planned to do at an underground laboratory in order to get free from neutral particles originating from cosmic-rays. In April 1984 we have made the background test at the experimental site of the proton decay at the Kamioka underground laboratory, and have checked the possibility of our measurement there. Then we moved the ELEGANTS to Kamioka in May 1984. We first built a house for experiments to avoid the dust and the humidity. In the room an air-conditioning and a de-humidifier have been operated all day long to keep the room temperature and humidity at constant values, typically 23 ^{0}C and 65 %. AC power lines were provided from the Mitsui Metal Ind. Ltd., which owns the Kamioka mine.

The second run (RUN 2) started in August 1984. and ended November 1984. Since the counting rate at Kamioka is 0.06 per sec.

and is only 1/20 of that at Osaka, it was possible to continue a measurement for about two monthes without an exchange of a magnetic tape. Actually every measurement ran by itself for about 10 days, recording a data in the magnetic tape and the disk. The period corresponds to the cycle of a liquid N_2 supply. Thus one of our group visited the Kamioka laboratory every 10 days to supply the liquid N_2, to check the experimental conditions and to bring the data in the magnetic tape.

The measurement for the energy calibrations of the NaI detectors were done as in the RUN 1. We did not observe any peak at 511 keV, but found a small 609 keV peak from the decay of ^{214}Bi for every calibration run. It was used instead of 511 keV peak.

The background rates for $0^+ \rightarrow 0^+$ and for $0^+ \rightarrow 2^+$ transitions of ^{76}Ge are 6.5×10^{-4} and 1.6×10^{-4} /keV·hr, respectively. Both of them are improved by a factor 3 ∿ 4 compared with those at the sea-level Osaka.

Here we encountered troubles characteristic at the underground laboratory. Some of them are as follows.

(1) Due to the very low counting rate, the electric noise about 1 Hz is enough to disturb our measurement. We wrapped the electronics and detectors by Aluminium sheets with great care. We had to avoid all kind of 'noisy' equipments, such as a buzzer, moters, etc. during the measurement. It is noted that 20 ∿ 30 percent of recorded events on magnetic tapes are caused by noises.

(2) Sometimes we had the AC power troubles, namely the AC power shut down, or the voltage down for an instant. We had to be careful to the increase of the humidity after the stop of the air-conditioning

(de-humidifier) as well as the damage of the computer and electronics. Even in such accidents, the measured data were saved in a magnetic tape for our case.

3-3-4 RUN 3 at the Kamioka underground without mercury shield

We were surprised at finding the 2043.7 keV peak in the $0^+\rightarrow0^+$ spectra of both the RUN 1 and the RUN 2. It was due to the ^{194}Hg isotope contained in the mercury shield around the NaI detectors. [Appendix A] Then the mercury shield was removed. It was at this time that lucite blocks are put in the space between the Ge and the NaI detectors in order to decrease the Radon gas in the air around the Ge detector. The third run (RUN 3) started in November 1984. Up to now (January 1986) measurements of about 7000 hours have been made. The total period of the RUN 2 and the RUN 3 at the Kamioka underground is about 8600 hours.

The background rates for $0^+\rightarrow0^+$ and for $0^+\rightarrow2^+$ transitions of ^{76}Ge are 6.2×10^{-4} and 2.7×10^{-4} /keV•hour, respectively. The rate for $0^+\rightarrow2^+$ transition seemed to get worse than that of the RUN 2. This might be due to the radioactive contamination contained in lucite blocks.

3-4 Analyses and results for the $0\nu\beta\beta$ decay of ^{76}Ge

3-4-1 The selections for true events

The selection rules for true events, namely the $0\nu\beta\beta$ $0^+\rightarrow0^+$ and $0^+\rightarrow2^+$ transitions of ^{76}Ge, from a sea of backgrounds are introduced as follows. For the $0^+\rightarrow0^+$ transition, signals from surrounding 4π-NaI detectors and from plastic scintillators are used for the anticoincidence with time interval of 10 μsec., since no γ-ray is accompanied by the $0^+\rightarrow0^+$ transition. For the $0^+\rightarrow2^+$ transition, the coincidence with the 559 keV γ-ray from one of six NaI segments is required. since the de-exciting 559 keV γ-ray from the first excited 2^+ state of ^{76}Se is accompanied by the $0^+ \rightarrow 2^+$ transition. It is noted that requiring the multiplicity of 1 (only one segment is fired) makes the background rate to a very low level. The energy window for the 559 keV γ-ray used for the coincidence (gating) with the Ge signal should be determined from the energy resolution of the NaI detectors at that energy. Assuming that the response of the NaI detector for 559 keV γ-rays is the Gaussian and the continuum background rate is proportional to the width of the window, 1.2×FWHM is the best choice. It is about 70 keV for our case and corresponding probability that the 559 keV γ-rays fall in this energy window is 84 %. Actually the response of every NaI detector is the Gaussian with a tail at lower energy side. It is considered to be the contribution from the multi-compton events. Taking into account this effect, the window of 100 keV is used. This is the reason that at the first analysis for the RUN 1 the energy window of 70 keV was used, and later we adopted that of 100 keV. The overall detection efficiency for the $0^+ \rightarrow 0^+$ transition (k_0) is 1, while for the $0^+ \rightarrow 2^+$ transition (k_1) is 0.34 at all. The induction of these coefficients is given in Chapter 2-4-2 in detail.

3-4-2 The energy resolution

All the measurements have been checked for energy resolutions and counting rates to check the reliability. Since there is a slight change in the gain of the Ge detector during thousands of hours, a direct summation of all the spectra causes a considerably worse energy resolution. In order to avoid this problem the summation is made only for the limitted energy region between (and around) the referenced 2 ∿ 3 peaks, which are used for the energy calibration for every run. This method provides good resolutions for the measurements of such long period. The energy resolutions versus the energy is shown for typical γ-ray peaks from backgrounds in Fig. 3-1. The resolutions for the RUN 2 and the RUN 3 at the energies of our interest are considered to be 2.5 keV for $Q_{\beta\beta}(0^+ \rightarrow 2^+) \simeq 1482$ keV and 3.0 keV for the $Q_{\beta\beta}(0^+ \rightarrow 0^+) \simeq 2041$ keV, respectively.

3-4-3 Resultant spectra for the $0\nu\beta\beta$ decay of ^{76}Ge

The enlarged spectra around the energies of $Q_{\beta\beta}(0^+ \rightarrow 0^+) \simeq 2041$ keV and $Q_{\beta\beta}(0^+ \rightarrow 2^+) \simeq 1482$ keV are shown in Fig. 3-2. In the figure (a) is the result of the RUN 1 at the sea-level Osaka for 2115 hours, (b) is the RUN 2 at the Kamioka underground for 1600 hours, and (c) is the RUN 3 also at the Kamioka underground for 6977 hours. As is already discussed, the peaks in the $0^+ \rightarrow 0^+$ spectra of the RUN 1 and the RUN 2 are attributed to the decay of ^{194}Hg. [Appendix A] There are no appreciable peaks due to the $0\nu\beta\beta$ decay of ^{76}Ge. In the $0^+ \rightarrow 0^+$ spectrum for the RUN 3 a peak is found at the energy of 2054 keV. Since it is not found in the spectrum for the RUN 2, it may be due to the radioactivities contained in the lucite blocks.

3-4-4 The lower limits on the $0\nu\beta\beta$ halflives

One must be very careful to deal with a small number of counts appeared in such spectra as shown above, because the statistics of them obey the Poisson distribution instead of the Gaussian distribution. The possible counts of the $0\nu\beta\beta$ peak hidden in the continuum of the background should be evaluated under the rule of the Poisson distribution as follows. The background counting rate around the $Q_{\beta\beta}$ energy, where there are no discrete lines, is evaluated well by averaging the yields around that energy region. Assuming the Poisson distribution for the possible yield of the true $0\nu\beta\beta$ events Y_T, one can get the probability that actually observed yield Y is the sum of the true events Y_T and the background Y_{BG}, i.e. $Y = Y_T + Y_{BG}$. Then, the 68 % probability for the $Y_T < Y_T^0$ is regarded as the upper limit of Y_T^0 for the $0\nu\beta\beta$ events at 68 % confidence level (C.L.). An example and more descriptions are given in Appendix B.

The halflife $T_{1/2}$ of the $\beta\beta$ decay of ^{76}Ge is expressed as follows.

$$T_{1/2} = 0.693 \times \frac{N_0 \cdot k_i \cdot t}{Y_T} \tag{3-1}$$

where N_0 is the number of ^{76}Ge source nuclei, k_i is the detection efficiency discussed in Chapter 2-4-2 and in Chapter 3-4-1, t is the measuring period in year, and Y_T is the possible hidden counts of the true $0\nu\beta\beta$ events just discussed above, respectively. All the parameters together with the background rate N_i(BG) and the energy resolution ΔE are summarized in Table 3-1. In the table halflives estimated from the sensitivity of the ELEGANTS are given. They show good agreement with those evaluated at 68 % C.L. by the procedure discussed above. (See Table 2-3(a) and (b)) The lower limits for the $0\nu\beta\beta$ decays were obtained by combinating data of both the RUNs 2 and 3, the sum of the running times being totally 8577 hours, at the underground laboratory. The limits on the halflives are 7.4×10^{22} (4.3×10^{22}) years for the $0^+\to0^+$ and 5.6×10^{22} (2.9×10^{22}) years for the $0^+\to2^+$ transitions, respectively, both on the 68 % (90 %) C.L.. The former is the same order of magnitude as the values of $(5\sim12)\times10^{22}$

years obtained by quit different types of detectors. (Belloti84b, Simpsom84, Forster84, Avignon85, Caldwell85) The latter sets a quit stringent limit on the $0\nu\beta\beta$ process far beyond the previous data of $(0.2\sim2.2)\times10^{22}$ years. (Belloti84b, Simpson84, Leccia83)

A preprint appeared very recently, in which the UCSB/LBL group reports the halflife limits of the ^{76}Ge $0\nu\beta\beta$ decay 2.5×10^{23} years for the $0^+\to0^+$ transition and 5×10^{22} years for the $0^+\to2^+$ transition, respectively. (Caldwell86) The former exceeds much the values reported previously, and the latter has the same order of magnitude of our experiment. The statistics of their data, however, are not good. The sensitivity of their detector are not comparable with their claimed results.

3-5 Limits on the neutrino mass and right-handed current

The present halflife limit for the $0^+\to0^+$ transition of ^{76}Ge is used to evaluate the upper limits on the neutrino mass and the right-handed current. Here the formula developed by Doi et. al. is used. (See Chapter 1-2) We assume that the coefficients of left-right cross term is zero for simplicity, namely $z = 0$ ($\eta = 0$). The numerical values of C_i's etc. used in Eq. 1-7 are given in the reference (Doi84). Then the Eq. 1-7(a) is given as

$$T_{0\nu}(0^+\to0^+)^{-1} = \log_e 2\cdot |M^{0\nu}_{GT}|\cdot(x^2 - 0.28xy + 2.8y^2) \qquad (3-2)$$

where x and y correspond to the neutrino mass and right-handed current. (See Eq. 1-6) The $M^{0\nu}_{GT}$ is given as 1.6×10^{-13} by Haxton (Haxton84), 2.8×10^{-14} for the corrected value by Doi, Kotani et. al. (Doi84), and 4.0×10^{-13} for the recent calculation by Grotz (Grotz83). The correction by Doi et. al. was made on the basis of the observed $2\nu\beta\beta$ value in the other nucleus. The present limit of the 7.4×10^{22} years (68 % C.L.) leads to the upper limits of 5.6 eV and 0.6×10^{-5} by Haxton, 3.6 eV and 0.4×10^{-5} by Grotz, and 13.6 eV and 1.6×10^{-5} by Kotani, respectively, on the neutrino mass and right-handed coupling term. The halflife limit of the 4.3×10^{22} years (90 % C.L.) gives the upper limits of 7.4 eV and 0.9×10^{-5} by Haxton, 4.7 eV and 0.5×10^{-5} by Grotz, and 17.7 eV and 2.1×10^{-5} by Kotani, respectively. The bounds for x (neutrino mass term) and y (right-handed coupling term) are shown on the x-y plane in Fig. 3-3. The matrix elements contributing to the $0^+\rightarrow2^+$ transition are not yet well evaluated now. A precise theoretical calculations are strongly appreciated as well as accurate experiments.

CHAPTER 4 Discussions and Related Topics

4-1 The mass of the neutrino

4-1-1 Methods to measure the neutrino mass

Recently much attentions have been paid on the property of the neutrinos emitted in a weak decay, especially on the mass of the neutrinos (m_ν). From the theoretical views, the simplest theory based on the minimal $SU(2)_L \times U(1)$ model predicts zero masses, while grand unified theories with the lepton-hadron universality and the left-right symmetry provide finite neutrino masses. From the experimental views, the first evidence of non-zero neutrino mass of $14 \text{ eV} \leq m_\nu \leq 46 \text{ eV}$ was reported by ITEP (Moscow) group, studying the tritium β-decay in 1980 (Lubimov80). Doi et. al. also estimated the neutrino mass around 30 eV from the geochemical ββ experiment by Hennecke et. al.. Therefore the experiments to confirm the finite reported value of the neutrino mass have been made so far by several different methods. However, there have been no positive results of the non-zero neutrino masses, except for the ITEP's one.

In recent years many review articles on this field have been published. Some of them are given in references, Wu80, Frampton and Vogel (Frampton82), Bullock and Devenish (Bullock83), Boehm and Vogel (Boehm84), ... and so forth. The talks at the related conferences were also useful to know the perspective of this field. Examples are found in talks at 'Low Energy Test of Conservation Laws' (Vuilleumier83), at 'International Lepton Photon Symposium' (Shaevitzi83) etc., and individual talks presented at the Moriond workshop in 1984.

In the followings methods to get the knowledge on the neutrino masses are briefly given.

(1) Tritium β-decay ... Study of the β-ray spectrum at the end point energy. This method gives the mass of the electron-type antineutrino ($\overline{\nu_e}$). (See Chapter 4-1-2)

(2) Electron capture ... Electron capture process to highly excited level is also good candidate to measure the m_ν. This method gives the mass of the electron-type neutrino (ν_e). For more details, see Chapter 4-1-3.

(3) Neutrino oscillations ... Neutrino oscillations occur if the weak eigenstates are not the mass eigenstates, but superposition of them. Then the abundance of one type of neutrinos contained in the beam will change as a function of the flight distance. This gives information on the difference between the squares of two types of neutrino masses and the mixing coefficients. Here we will not discuss in detail on this subject, but gives some references as a summary of these experiments. (Wu80, Frampton81) We just note a nice experiment at BNL by Nagashima's group.

(4) Cosmology and astrophysics ... Cosmological and astrophysical data can derive the restrictions on elementary particle properties. Actually they provide information on the number of neutrino families, masses, and their lifetimes. See Chapter 4-1-4.

(5) Neutrino-less double beta decay ... Neutrino-less double beta decay (0νββ) do not conserve the lepton number. This leads to the idea of Majorana neutrino, namely $\nu_e = \overline{\nu_e}$. The constraints on the neutrino mass from the 0νββ decay experiments is well discussed in Chapter 1-2. The measurements of the 0νββ decay is already summarized and discussed in Chapter 1-3. The possibility of heavy

neutrinos and the measurements for masses of μ-type and τ-type neutrinos are not discussed here for simplicity. The overviews of this field are found in the above quoted references.

4-1-2 Tritium β-decay

The tritium (^3H) β-decay can induce the mass of electron-type antineutrino by measuring β-rays near the end point energy. Tritium is the best choice among the β-decay sources for this purpose because of low end point energy (Q = 18.6 keV), low Z and convenient halflife ($T_{1/2}$ = 12.3 years).

Bergkvist et. al. (Bergkvist72) and Tretyakov et. al. (Tretyakov76) used electro-magnetic β-ray spectrometers. They gave limits of less than 55 eV and 33 ev, respectively, on the electron-type antineutrino mass. Simpson implanted the tritium in a Si(Li) detector, and obtained the mass less than 60 eV (Simpson81). The sensitivity of this experiment is limited by the resolution of the Si(Li) detector.

It was very impressive that the first experimental evidence of non-zero neutrino mass was announced by Lubimov et. al. in 1980 (Lubimov80). The source was an organic material 'valin' ($C_5H_{11}NO_2$) enriched with ^3H. The spectrometer was an iron-free thoroidal type. In 1983 they made the measurement with an improved spectrometer and reported m_ν > 20 eV (Boris83). Again in 1984 they claimed that m_ν > 9 eV on the 90 % confidence level by the model independent analyses. Critical points of these experiments are the evaluation of the atomic final state population of the daughter $^3H^+$ atom, and the response function curve of the β-ray measuring system. The typical results obtained so far from these experiments are given in Table 4-1.

The situation in tritium β-decay is still not clear. Several groups are working hard with the tritium experiment. Some of them use frozen (or cooled) tritium atom ($^3H_2$)to avoid the problem of atomic interplay (Fackler84-85, Kawasaki85), since the final states of the tritium atom can be well calculated. Los Alamos group uses the atomic beam of tritium in order to be free from all kinds of final states problems (Bowles82-83, Robertson84). The plans at present are given in Table 4-2 together with references. The goal of them is the neutrino ($\overline{\nu_e}$) mass around 10 eV.

4-1-3 Electron Capture

Electron capture is also useful to detect a finite mass of the electron-type neutrino. The problems on the atomic interplay and the atomic states populations are not so serious on this methods, compared with the tritium β-decay experiments. In fact the m_ν sensitivity of 0.2 ∿ 0.4 eV is expected by this method, which is better than that of the tritium β-decays by a factor of 10. Because of its low Q-value (Q ≃ 2.6 keV), ^{163}Ho is the most attractive source in this experiments.

There are two ways to approach to the finite neutrino mass. The first type was proposed by De Rújula (De Rújula81). In this method the internal bremsstrahlung (IB) spectrum following electron capture (EC) is measured. The spectrum near the end point is sensitive to the neutrino mass.

$$A_Z + e^- \rightarrow A_{Z-1} + \nu_e + \gamma_{IB}$$

The second type was discussed by Bennett et. al. (Bennett81). It measures the relative rate of captures, which depend on the neutrino mass.

Among them Yasumi et. al. studied the ratio of the electron capture decay constants, $\lambda(M1)$ and $\lambda(M2)$ (Yasumi85). It is expected that the previous values will be considerably revised in early 1986. Recently an electron capture of ^{158}Tb with extremely low Q-value (Q = 156 eV) was reported (Raghavan83). The first type experiment with ^{158}Tb is also expected to give better results.

4-1-4 Constraints from cosmology

The number of neutrino flavors can be determined from the amount of ^{4}He produced in the big-bang nucleosynthesis (Shvartsman69). However, it is difficult to estimate an accurate value of the primordial abundance of ^{4}He. Recent studies lead to the result that the number of neutrino flavours is not more than 4 (OLive81, Steigman84).

The constraints on the masses of neutrino are obtained by the observed deceleration of the expansion rate of the Universe. It sets the limit to the sum of all stable neutrino masses in the range 50 $\sim$ 100 eV (Cowsik72, Marx72) These works also provide the idea that neutrinos are responsible for the dark matter halo of galaxies and clusters.

Tremaine and Gunn showed that all the dark matter could be neutrinos if one-type neutrino had a mass greater than 20 eV or if sum of all types of neutrino mass is greater than 20 eV (Tremaine79). However, Schramm and Steigman showed that some of the dark mass is baryonic and neutrinos need not supply all the dark mass (Schramm81).

Because neutrinos are regarded as relics from the time of big-bang, the constraints on neutrino properties greatly depend on the scenarios describing the early evolution of the Universe. It is interesting that some of the scenarios require the massive neutrinos. Such massive neutrinos play a very important role in the growth of the Universe (Olive81). The recent activity of this field has been very high. Then further theoretical attempts may provide new constraints on the neutrino properties. Thus cosmologists have great interest in elementary particle experiments on the neutrino masses (Dolgov81).

4-2 ELEGANTS as an ultra-low background system

4-2-1 Double beta decays of other isotopes with the ELEGANTS

A unique point of the ELEGANTS for the $0\beta\beta$ of ^{76}Ge is that the Ge detector itself contains the ^{76}Ge $\beta\beta$ source. The decay rate of ^{76}Ge, however, is not large because both the $Q_{\beta\beta}$ value and the $\beta\beta$ matrix element are small. There are a number of $\beta\beta$ source nuclei with large $Q_{\beta\beta}$ values and/or large $\beta\beta$ matrix elements. The ELEGANTS can be used for these other $\beta\beta$ nuclei by using a mosaic $\beta\beta$-source and Si-detector ensemble instead of the Ge detector. Actually the Ge detector is replaced by ten ^{100}Mo foils sandwitched by eleven Si detector array. The detector and source ensemble is shown in Fig. 4-1. The energy resolution is mainly due to the thickness of the foil. It is about 50 keV. On the other hand the transition rate for ^{100}Mo is an order of magnitude larger than that of ^{76}Ge, and one β-ray can be measured in coincidence with another β-ray. These merits can compensate the demerits of the finite source thickness and the smaller amount of ^{100}Mo nuclei than that of ^{76}Ge. All detectors and ^{100}Mo foils are now set, and the run will start soon within next 2-3 weeks.

4-2-2 Rare γ-decays and weak radioactivities

The ELEGANTS can be used not only for the $0\nu\beta\beta$ search but also for detecting very rare γ-decays and very weak radioactivities. By drawing back the Ge detector by 1 cm from the well of the 10" NaI, one can insert a 9 cm × 1 cm material which contains γ-active isotopes. Then the γ-activity can be measured with the Ge detector in various modes of the NaI detectors. (See Chapter 2-4 for modes of the ELEGANTS)

The sensitivity for the weak γ-decay is then obtained in a similar way as for the $0\nu\beta\beta$ (see Eq. 2-1). In case that the weak γ_0-ray is accompanied by γ_1, γ_2, ..., the γ_0 is detected by the Ge detector while the γ_1, γ_2, ... are detected by the six segment NaI detectors to identify the γ_0 event. Then the sensitivity of detecting the γ_0 is given by

$$\varepsilon_i(RI) = 1.12\times10^{-18}\sqrt{N_i(BG)\cdot\Delta E} \;/\; (k_\gamma\cdot k) \qquad (4\text{-}1)$$

where k_γ is the peak efficiency of the Ge detector for the γ_0, k is the detector efficiency of the 4π-NaI counter for γ_1, γ_2, ... associated with the γ_0, the $N_i(BG)$ is the background rate of the Ge detector at $E(\gamma_0)$ per year per unit energy for the Ge detector at $E(\gamma_0)$ and ΔE is the energy resolution. The lower limit on the γ-activity which can be detected for the running time of t years is given by

$$N_t = \frac{\varepsilon_i}{y\sqrt{t}} \text{ (Curie)} \qquad (4\text{-}2)$$

where y is the fraction of the γ_0 being accompanied by the γ_1, γ_2,

Sensitivities for typical γ-rays of 1, 2, and 3 MeV are given for various decay modes in Table 4-3(a) and (b). The value of $\varepsilon \sim 0.1\times10^{-15}$ in the table means that an activity of $\sim 10^{-15}$ Curie can be detected when it is measured for one week at the Kamioka underground laboratory. For a typical source with thickness of about 10 gram/cm^2 and the atomic number Z=50, the absorption is small and the lower limit of γ-activities which can be measured for about one year running time is approximately given by ε. Assuming the source size of 9 cm $\phi\times$ 1 cm and the density of 8 gram/cm^2, the specific activities are given by $2\times10^{-3}\cdot\varepsilon$ Curie/gram.

A sensitivity for detecting natural radioactivity is written by

$$\varepsilon_i(\mathrm{NRI}) = 0.855\times10^{-18}\sqrt{N_i(\mathrm{BG})}\ /\ (k_\gamma\cdot b_i) \qquad (4\text{-}3)$$

where b_i is the branching ratio (probability) of the γ-emission for the decay mode i, and $N_i(\mathrm{BG})$ is the γ-ray peak yield per year in the background spectrum for the mode i. Sensitivities for typical radioactive isotopes of ^{40}K, ^{208}Tl and ^{214}Bi are given in Table 4-4. A lower limit of detecting a radioactivity is given by Eq. 4-2 with y=1 as in case of a rare γ decay.

Chapter 5 Concluding remarks

The ELEGANTS (ELEctron GAmma-ray NeuTrino Spectrometer) has been developed and constructed successfully to search for very rare events of the 0ν (neutrino-less) $\beta\beta$ decay. The sensitivity of the ELEGANTS, which is introduced in Chapter 2, for the $0\nu\beta\beta$ decay of ^{76}Ge is one of the highest values for the $0^+\rightarrow0^+$ transition, and is best in the world for the $0^+\rightarrow2^+$ transition. It is important that the 4π-NaI γ-detector plays an essential role in selecting the true $0\nu\beta\beta$ events from a large amount of backgrounds. Actually the continuum background components are reduced by factors of 1.4×10^4 and 1.1×10^5 at the energies of the $0^+\rightarrow0^+$ and the $0^+\rightarrow2^+$ transition, respectively.

There found no appreciable peak at the energies of the $0\nu\beta\beta$ decay from the measurement for 8577 hours at the Kamioka underground laboratory. The lower limits on the halflives are obtained as 7.4×10^{22} (4.3×10^{22}) years for the $0^+\rightarrow0^+$ transition, and 5.6×10^{22} (2.9×10^{22}) years for the $0^+\rightarrow2^+$ transition, both at 68 % (90 %) confidence level. The corresponding upper limits for the neutrino mass and the right-handed coupling term depend much on the nuclear matrix element used. According to the nuclear matrix element calculated by Haxton (Haxton84), the present experimental halflife provides following limits

$$\langle m_\nu \rangle = 5.6 \text{ eV } (7.4 \text{ eV}), \quad y < 0.6\times10^{-5} \ (0.9\times10^{-5})$$

where $\langle m_\nu \rangle$ and y correspond to the neutrino mass and right-handed coupling. (See Eq. 1-6) The brackets show the values evaluated at 90 % confidence level. While the corrected matrix element by Doi et. al. gives

$$\langle m_\nu \rangle = 13.6 \text{ eV } (17.7 \text{ eV}), \quad y < 1.6\times10^{-5} \ (2.1\times10^{-5})$$

On the other hand another calculation of the matrix element by Grotz (Grotz83) leads to the following limits

$\langle m_\nu \rangle = 3.5$ eV (4.7 eV), $y < 0.4\times10^{-5}$ (0.6×10^{-5})

The finite neutrino mass of 36±4 eV has been reported from the tritium β-decay experiments (Boris83, Lubimov80). On the other hand the neutrino mass determined from electron capture experiments are less than 240 eV at present (Bennet84). Note that tritium β-decays report the mass of electron-type antineutrino ($\overline{\nu_e}$), while electron capture experiments refer to the mass of elctron-type neutrino (ν_e). However, neutrino-less double beta decays assume that the neutrino is a Majorana particle ($\nu\equiv\overline{\nu}$) and obtained mass is the superposition of the masses of mass eigenstate neutrinos with weights of weak-eigenstate neutrino mixing. (See Eq. 1-6) The consistency between them should be well discussed, taking into account the types of neutrinos and the experimental confidence levels. At present it is too early to draw convincible pictures on the properties of neutrinos. Further advances both in experiments and in theories are desired.

Actually there are several new experiments on the neutrino masses under progress or under planning. They are expected to clarify this problem. As for the double beta decays, one way is to increase the amount of the ^{76}Ge ββ source. Two groups (PNL/USC, UCSB/LBL) have plans with about totally 1000 cc Ge assembly (Caldwell85, Avignon85). It is interesting that one group (UCSB/LBL) uses the 4π-NaI counter as is the ELEGANTS, while another (PNL/USC) does not. The latter group gave up the use of NaI detectors because they brought radioactivities into quite near position of the Ge detector (Brodzinski85). The activities contained in the NaI detector is also reported by us. (Chapter 2) In fact it is the main background source of the ELEGANTS at present. These experiments with Ge detectors can not measure the angular correlation between two electrons and the energy distribution of single electron, although the detection efficiency is 100 % and the resolution is very high. The other way is to use other ββ nuclei with large $Q_{\beta\beta}$ value and/or larger nuclear matrix elements. Measurement of energy and angular distributions with new experimental techniques are important.

Three types of new ββ experiments are now under progress in our laboratory.

(1) The measurement of the 0νββ decay of ^{100}Mo with with 11 Si(Li) detectors will soon start instead of the Ge. (See Chapter 4-2-1 and Fig. 4-1) The thin foils of enriched ββ source nuclei are sandwiched between the Si(Li) detectors. This multi-layer structure has following benefits. (a) The effective amount of ββ source is large. (b) The energy distribution of β-rays can be measured. The rough correlation of directions of two electrons is also measurable. (c) One can easily measure the other ββ source by replacing the source foils by those of the other ββ nuclei. ; The whole detector assembly of the ^{100}Mo foils and the Si(Li) detectors are placed inside the 4π-NaI counter used for the ELEGANTS. The goal of this experiment is the same order or better than that of the Ge.

(2) The ββ decay of ^{130}Te has been measured at the sea-level laboratory of Osaka Univ. since Dec. 1985. The detectors for β-rays are the six-layer plastic scintillator plates. Five layers of the natural Te powder are set between these scintillators. The γ-rays

following the β-rays are detected by the surrounding 4π-NaI counter. The whole plastic and NaI system is shielded from external γ-rays by means of heavy metallic shields. The veto counter is also mounted around the heavy shield. The measurement for 1∼2 months with both the Te source and the dummy sample is expected to provide the halflife limit of 10^{20}∼10^{21} years. This experiment is regarded as the prototype for the next (3-rd) experiment.

(3) We have another plan to measure the 0νββ decays of ^{150}Nd and ^{100}Mo with a completely new ELEGANTS. The central part of the new ELEGANTS is layers of drift chambers. The source foils containing about 10^{24} ββ nuclei are placed between them. The β-rays are detected by thin NaI scintillators. The whole detecting system is surrounded by 4π-NaI detectors for γ-rays. Copper and lead shields are mounted around the detectors to reject external γ-ray backgrounds. The new system is expected to have an ability to determine the neutrino mass of about 1 eV.

References

1. General references : Proceedings of Conferences. Headings of the proceedings, as given below, are used in individual references.

BLACKSBURG83 : Low Energy Test of Conservation Law, Blacksburg, Sept. 1983, AIP Conf. Proc. No.114 (1984)

HEP83 : Int. Europhysics Conf. high Energy Physics (HEP83), Brington (UK), July 1983, edited by J. Guy and C. Costain, (1983)

LOSALAMOS83 : Sience Underground, Los Alamos, 1983, AIP Conf. Proc. No.96 (1983)

MORIOND84 : Massive Neutrinos in Astrophysics and in Particle Physics (Proc. 4-th. Moriond Workshop), Jan. 1984, Moriond, edited by J. Thanh Van, Editions Frontieres, (1984)

MORIOND85 : Perspectives of Electroweak Interactions (Proc. Leptonic Session 20-th. Moriond Workshop), March 1985, Moriond, edited by J. Thanh Van, Editions Frontieres, (1985)

NEUTRINO72 : Proc. Int. Conf. Neutrino Physicsand Astrophysics, Hungary, June 1972, edited by A. Frenkel and G. Marx, (1972)

NEUTRINO76 : Proc. Int. Conf. Neutrino Physicsand Astrophysics, Aachen, June 1976, edited by H. Faissner, H. Reithler and P. Zerwas, Vieweg, (1976)

NEUTRINO82 : Proc. Int. Conf. Neutrino Physics and Astrophysics, Budapest, June 1982, edited by A. Frenkel and L. Jenik, (1982)

NEUTRINO84 : Proc. Int. Conf. Neutrino Physics and Astrophysics, Dortmunt, June 1984, edited by K. Kleinknecht and E.A. Paschos, World scientific, (1984)

OSAKA84 : Proc. Int. Symp. Nucl. Spectroscopy and Nucl.

Interactions, March 1984, Osaka, World Scientific, edited by H. Ejiri and T. Fukuda, (1984)

PROVIDENCE84 : Proc. 5th. Workshop on Grand Unification, Providence, R.I., April 1984, World Scientific, edited by K. Kang, H. Fried and P. Frampton, (1984)

SANTA FE84 : Proc. Session of Neutrino Mass and Related Topics, APS Meeting on Particles and Fields, Santa Fe, Nov. 1984, edited by P. White

TELEMALK82 : Neutrino Mass and Gauge Structure of Weak Interactions, 1982, Telemalk, AIP Conf. Proc. No.99 (1983)

TELEMALK84 : Proc. Int. Conf. Neutrino Mass and Low Energy Weak Interactions, Telemalk, Oct. 1984, World Scientific, edited by V. Barger and D. Cline, (1985)

2. Individual references

Anderson82 : J.U. Anderson, G.J. Beyer, G. Charpak, A. De Růjula, B. Elbek, H.A. Gustafsson, P.G. Hansen, B. Jonson, P. Knudsen, E. Laegsgaard, J. Pedersen and H.L. Ravn, Phys. Lett. 113B(1982)72

Antonio60 : G.F. Dell'Antonio and E. Fiorini, Suppl. Nuovo. Cim. 17(1960)830

Avignon83 : F.T. Avignone, R.L. Brodzinski, D.P. Brown, J.C. Evans Jr., W.K. Hensley, J.H. Reeves and N.A. Wogman, Phys. Rev. Lett. 50(1983)721;

Avignon85 : F.T. Avignone , R.L. Brodzinski, D.P. Brown, J.C. Evans Jr., W.K. Hensley, H.S. Miley, J.H. Reeves and N.A. Wogman, Phys. Rev. Lett. 54(1985)2309

Bellotti82 : E. Bellotti, E. Fiorini, C. Liguori, A. Pullia, A. Sarracino and L. Zanotti, Lett. Nuovo Cim. 33(1982)273;

Bellotti83 : E. Bellotti, E. Fiorini, C. Liguori, A. Pullia, A. Sarracino and L. Zanotti,, Phys. Lett. 121B(1983)72;

Bellotti84b : E. Bellotti, NEUTRINO84, (1984)p.171

Bellotti84b : E. Bellotti, O. Cremonesi, E. Fiorini, C. Liguori, A. Pullia, A. Sverzellati and L. Zanotti,, Phys. Lett. 146B(1984)450

Bennett81 : C.L. Bennett, A.L. Hallin, R.A.Naumann, P.T. Springer, M.S. Witherell, R.E. Chrien, P.A. Baisden and D.H. Sisson, Phys. Lett. 107B(1981)19

Bennett84 : C.L. Bennett, TELEMALK84, (1985)p.128

Bergkvist72 : K.E. Bergkvist, Nucl. Phys. B39(1972)317

Bergkvist84 : K.E. Bergkvist, MORIOND84, (1984)p.243

Boehm84 : F. Boehm and P. Vogel, Ann. Rev. Nucl. Part. Sci.

34(1984)125

Boris83 : S. Boris, A. Golutvin, L. Laptin, V.A. Lubimov, V. Nagovizin, E. Novikov, V. Nozik, V. Soloshenko, I. Tichomirov and E.F. Tretyakov, HEP83, (1983)p.386

Bowles82 : T. Bowles et. al., TELEMALK82, (1983)p.17

Bowles83 : T. Bowles et. al., BLACKSBURG83, (1983)P.212

Brodzinski85 : R.L. Brodzinski, D.P. Brown, J.C. Evans Jr., W.K. Hensley, J.H. Reeves, N.A. Wogman, F.T. Avignone and H.S. Miley, Nucl. Inst. Meth. A239(1985)207

Bullock83 : F.W. Bullock and R.C.E. Devenish, Rep. Prog. Phys. 46(1983)1029

Caldwell85 : D.O. Caldwell, R.M. Eisberg, D.M. Grumm, D.L. Hale, M.S. Witherell, F.S. Goulding, D.A. Landis, N.W. Madden, D.F. Malone, R.H. Pehl and A.R. Smith, Phys. Rev. Lett. 54(1985)281

Caldwell86 : D.O. Caldwell, R.M. Eisberg, D.M. Grumm, D.L. Hale, M.S. Witherell, F.S. Goulding, D.A. Landis, N.W. Madden, D.F. Malone, R.H. Pehl and A.R. Smith, Half-life limits on the zero- neutrino and two-neutrino double beta decay of ^{76}Ge, Univ. of California, preprint

Cowsik72 : R. Cowsik, J. McClelland, Phys. Rev. Lett. 29(1972)669

De Rújula81 : A. De Rújula, Nucl. Phys. B188(1981)414

Doi81 : M. Doi, T. Kotani, H. Nishiura, K. Okuda and E. Takasugi, Prog. Theor. Phys. 66(1981)1739,1765

Doi83a : M. Doi, T. Kotani, H. Nishiura and E. Takasugi, Prog. Theor. Phys. 69(1983)602

Doi83b : M. Doi, .M. Kenmoku, T. Kotani, H. Nishiura and

E. Takasugi, Prog. Theor. Phys. 70(1983)1331

Doi83c : M. Doi, T. Kotani, H. Nishiura and E. Takasugi, Prog. Theor. Phys. 70(1983)1353

Doi84 : M. Doi, T. Kotani and E. Takasugi, TELEMARK84, (1985) in press; OS-GE 84-09, Osaka Univ. Preprint (1984)

Dolgov81 : A.D. Dolgov and Y.B. Zeldovich, Rev. Mod. Phys. 53(1981)1

Ejiri84 : H. Ejiri, N. Takahashi, T. Shibata, Y. Nagai, K. Okada, N. Kamikubota and T. Watanabe, OSAKA84, (1984)p.284

Ejiri85a : H. Ejiri, N. Kamikubota, Y. Nagai, K. Okada, T. Shibata, N. Takahashi and T. Watanabe, TELEMARK84, (1985) in press

Ejiri85b : H. Ejiri, N. Kamikubota, Y. Nagai, K. Okada, T. Shibata, N. Takahashi and T. Watanabe, SANTA FE84, (1985) in press

Ejiri86 : H. Ejiri, N. Takahashi, T. Shibata, Y. Nagai, K. Okada, N. Kamikubota, T. Watanabe, T. Irie, Y. Itoh and T. Nakamura, Nucl. Phys. A448(1986)271

Ellis84 : R.J. Ellis, B.J. Hall, G.R. Dyck, C.A. Lander, K.S. Sharma, R.C. Barber and H.E. Duckworth, Phys. Lett. 136B(1984)146

Fackler84 : O. Fackler, M. Mugge, H. Sticker and R. Woerner, MORIOND84, (1984)p.281

Fackler85 : O. Fackler, B. Jeziorski, W. Kolos, H. Monkhorst, M. Mugge, H. Sticker, K. Szalewicz, R.M. White and R. Woerner, MORIOND85, (1985)p.313

Fermi34 : E. Fermi, Zeits. f. Physik 88(1934)161

Fiorini72a : E. Fiorini, NEUTRINO72, (1972)p.99

Fiorini72b : E. Fiorini, Riv. Nuovo Cim. 2(1972)1

Fiorini73 : E. Fiorini and A. Pullia, Nuovo Cim. 13A(1973)747

Fiorini84 : E. Fiorini, PROVIDENCE84, (1984)p.283

Forster84 : A. Forster, H. Kwon, J.K. Markey, F. Boehm and H.E. Henrikson, Phys. Lett. 138B(1984)301

Frampton82 : P.H. Frampton and P. Vogel, Phys. Rep. 82(1982)339

Furry39 : W.H. Furry, Phys. Rev. 56(1939)1184

Gelmini81 : G.B. Gelmini and M. Roncadelli, Phys. Lett., 99B(1981)411

George81 : H.M. George, S.L. Glashow and S. Nussinov, Nucl. Phys. B193(1981)297

Grotz83 : K. Grotz, H.V. Klapdor and J. Metzinger, J. Phys. G9(1983)L169

Hartmann85 : F.X. Hartmann and R.A. Naumann, Phys. Rev. C31(1985)1594

Haxton81 : W.C. Haxton, G.J. Stephanson and D. Strottman, Phys. Rev. Lett. 47(1981)153; Phys. Rev. D25(1982)2360

Haxton84 : W.C. Haxton and G.J. Stephanson Jr., Progr. Part. Nucl. Phys., edited by D. Wilkinson, Vol.12(1984)p.409

Jagem85 : P. Jagem, J.J. Simpson, J.L. Campbell, B.C. Robertson and H.L. Malm, Nucl. Inst. Meth. A239(1985)214

Jonson83 : B. Jonson, J.U. Anderson, G.J. Beyer, G. Charpak, A. De Rújula, B. Elbek, H.A. Gustafsson, P.G. Hansen, P. Knudsen, E. Laegsgaard, J. Pedersen and H.L. Ravn, Nucl. Phys. A396(1983)479c

Kamikubota86 : N. Kamikubota, H. Ejiri, T. Shibata, Y. Nagai, K. Okada, T. Watanabe, T. Irie, Y. Itoh and T. Nakamura and N. Takahash, to be published in Nucl. Inst. Meth. A (1986)

Kawasaki84 : H. Kawasaki, T. Yasuda, T. Ohshima, K. Ukai, S. Shibata, I. Sugai, Y. Shoji, F. Naito, T. Suzuki, T. Nagafuchi and H. Taketani, INS Annual Report 1984, (1985)p.51

Kirsten83 : T. Kirsten, LOSALAMOS83, (1983)p.396

Kirsten84a : T. Kirsten, PROVIDENCE84, (1984)p.268

Kirsten84a : T. Kirsten, NEUTRINO84, (1984)p.145

Klapdor84 : H.V. Klapdor and K. Grotz, Phys. Lett. 142B(1984)323

Knoll79 : G.F. Knoll, Radiation Detection and Measurement, (Wiley, New York, 1979)

Kotani84a : T. Kotani, OSAKA84, (1984)p.259

Kotani84b : T. Kotani, MORIONDO84, (1984)p.397

Leccia83 : F. Leccia, Ph. Hubert, D. Dassie, P. Mennrath and M.M. Villard, Nuovo Cim. 78A(1983)50;

Liguori83 : C. Liguori, A. Sarracino, P.P. Sverzellati and L. Zanotti, Nucl. Inst. Meth. 204(1983)585

Lubimov80 : V.A. Lubimov, E.G. Novikov, V.Z. Nozik, E.F. Tretyakov and V.S. Kosik, Phys. Lett. 94B(1980)266

Mahapatra81 : R.N. Mahapatra and J.D. Vergados, Phys. Rev. Lett., 47(1981)1713

Marx72 : G. Marx and A.S. Szalay, NEUTRINO72, (1972)p.123

Mayer35 : M. Goeppert-Mayer, Phys. Rev. 48(1935)512

Olive81a : K.A. Olive, D.N. Schramn and G. Steigman, Nucl. Phys. B180(1981)497

Olive81b : K.A. Olive, D.N. Schramm, G. Steigman, M.S. Turner and J. Yang, Ap. J. 246(1981)547

Primakoff59 : H. Primakoff and S.P. Rosen, Rept. Progr. Phys. 22(1959)121

Primakoff65 : H. Primakoff and S.P. Rosen, in Alpha-, Beta, and Gamma-Ray Spectroscopy, edited by K. Siegbahn, North-Holland Pub., (1965)p.1499

Promakoff69 : H. Primakoff and S.P. Rosen, Phys. Rev. 184(1969)1925

Primakoff81 : H. Primakoff and S.P. Rosen, Ann. Rev. Nucl. Science, 31(1981)145

Raghavan83 : R.S. Raghavan, Phys. Rev. Lett. 51(1983)975

Ravn82 : H.L. Ravn, J.U. Anderson, G.J. Beyer, G. Charpak, A. De Rùjula, B. Elbek, H.A. Gustafsson, P.G. Hansen, B. Jonson, P. Knudsen, E. Laegsgaard and J. Pedersen, TELEMALK82, (1983)p.1

Ravn84 : H.L. Ravn, J.U. Anderson, G.J. Beyer, A. De Rùjula, P.G. Hansen, B. Jonson and E. Laegsgaard, MORIOND84, (1984)p.287

Rizzo82 : T.G. Rizzo, Phys. Rev. D25(1982)1355

Robertson84 : R.G.H. Robertson, T.J. Bowles, J.C. Browne, T.H. Burritt, J.A. Helffrich, D.A. Knapp, M.P. Maley, M.L. Stelts and J.A. Wilkerson, MORIOND84, (1984)p.253

Scheceter82 : J. Schechter and J.M.F. Valle, Phys. Rev. D25(1982)2951

Schramm81 : D.N. Schramm and G. Steigman, GRG 13(1981)101; Ap. J. 243(1981)1

Shaevitz83 : M. Shaevitz, Proc. 1983 Int. Symp. Lepton and Photon Interactions at High Energies, Cornell Univ., Aug. 1983, (1983)p.132

Shvartsman69 : V.F. Shvartsman, JETP Lett. 9(1969)184

Simpson81 : J.J. Simpson, Phys. Rev. D23(1981)649

Simpson84 : J.J. Simpson, P. Jagem, J.L. Campbell, H.L. Malm and B.C. Robertson, H.L. Malm, Phys. Lett. 53(1984)141

Steigman84 : G. Steigman, MORIOND84, (1984)p.295

Takaoka66 : N. Takaoka and K. Ogata, Z. Naturforsch 21A(1966)84

Tremaine79 : S. Tremaine and J.E. Gunn, Phys. Rev. Lett. 42(1979)407

Tretyakov76 : E.T. Tretyakov, V. Efremenko, N.F. Myasoedov, A.M. Apalikov, V.F. Konyaev, V.A. Lubimov and E.G. Novikov, Izv. Akad. Nauk SSSR Ser. Fiz. 40(1976)20; NEUTRINO76, (1976)p.663

Yasumi83 : S. Yasumi, G. Rajasekaran, M. Ando, F. Ochiai, H. Ikeda, T. Ohta, P.M. Stefan, M. Maruyama, N. Hashimoto, M. Fujioka, K. Ishii, T. Shinozuka, K. Sera, T. Omori, G. Izawa, M. Yagi, K. Masumoto and K. Shima, Phys. Lett. 122B(1983)461

Yasumi84 : S. Yasumi, F. Ochiai, M. Ando, H. Maezawa, H. Kitamura, M. Maruyama, M. Fujioka, K. Ishii, T. Shinozuka, K. Sera, T. Omori, G. Izawa, M. Yagi, K. Masumoto, K. Shima, T. Murayama, Y. Inagaki, H. Taketani, I. Sugai and A. Masuda, NEUTRINO84, (1984)P.202

Yasumi85 : S. Yasumi, M. Ando, H. Maezawa, H. Kitamura, T. Ohta, F. Ochiai, A. Mikuni, M. Maruyama, M. Fujioka, K. Ishii, T. Shinozuka, K. Sera, T. Omori, G. Izawa, M. Yagi, K. Masumoto, K. Shima, T. Murayama, Y. Inagaki, I. Sugai, A. Masuda and O. Kawakami, Oct. 1985, KEK Preprint 85-45

Vuilleumier83 : J.L. Vuilleumier, BLACKSBURG83, (1984)P.154

Wolfenstein82 : L. Wolfenstein, Phys. Rev. D26(1982)2507

Wu80 : C.S. Wu, Weak Interactions on Probes of Unification, Virginia, Dec. 1980, AIP Conf. Proc. No.72(1981)p.1

Zamick82 : L. Zamick and N. Auerback, Phys. Rev. C26(1982)2185

ACKNOWLEDGEMENTS

The author would like to thank Professor H. Ejiri for valuable discussions and suggestions throughout this work, as well as for his kind encouragement. He also expresses his best thanks to Dr.'s T. Shibata, Y. Nagai, K. Okada and N. Takahashi for their kind collaborations and discussions during the whole course of the experiments. The author is deeply indebted to all other people of the Ejiri's group at the Dept. Physics and OULNS for their sincere help at the transportation of the ELEGANTS from Osaka to Kamioka. They are the staffs (T. Fukuda, T. Motobayashi, and H. Ohsumi), graduated students (T. Watanabe, T. Irie, Y. Itoh, and T. Nakamura), the technical staffs (K. Matsuoka and K. Higa), and the secretaries (K. Mikamoto, Y. Tanuma and S. Tsuzuki). Actually it was an extremely hard work and it could never carried out without their helps.

The author and collaborators wish to thank Professors M. Koshiba, S. Miyake and K. Kamata of Institute for Cosmic Ray Research, and Dr. H. Suda of Univ. of Tokyo for their kind arrangements and encouragements at the Kamioka underground laboratory. It is worth to note that they gave us a warm welcome when we first asked for the permission of our experiment at Kamioka. We also thank the Mitsui Metal Ind. Ltd. and workers in that company for the help at the Kamioka underground environment.

Thanks are also due to Proffessors T. Kotani, M. Doi and E. Takasugi, who are the members of the theoretical group at College of General Education, Osaka Univ.. Their works in recent years are especially valuable in this field. They greatly encourage our experiment.

This work is supported in part by the Grant in Aid of Scientific research, Ministry of Education, Science and Culture, Japan, and the Tolay Science and Technology Grant.

APPENDIX A Evidence for ^{194}Hg isotope in natural mercury

The measurements on neutrino-less double beta decay of ^{76}Ge had been carried out first at the Osaka Univ. sea-level laboratory for 2115 hours, and next at the Kamioka underground laboratory for 1600 hours. We were surprised at obvious peaks at the energy of 2044 keV appeared in both the energy spectra which were obtained by completely independent measurements. Considering the energy of the line and the materials used for our detector system, we concluded that the line is due to the decay of ^{194}Hg. The γ-ray of 2043.7 keV from the decay of ^{194}Hg penetrates the NaI detector, and then it deposits the full energy in the Ge crystal. Fig. A1 shows the decay scheme of ^{194}Hg.(1) In what follows we explain how we identify the line.

Since data are recorded by an event by event list mode on magnetic tapes, We can select ^{194}Hg decay events efficiently from a large amount of backgrounds by using proper gate conditions in the offline analysis. Some kinds of gate conditions were investigated. We found the most clear evidence of ^{194}Hg in the Ge spectra measured in anticoincidence with surrounding NaI detectors. The spectra indicate clearly the lines characteristic of the decay of ^{194}Hg.

The relative counts of peaks are calculated for every line taking into account the absorption through the mercury layer and NaI detectors. These expected and observed counts are summarized in Table A1. Roughly speaking, they agree with each other. Calculated disintegration rate of ^{194}Hg is 3×10^{-2} per second. This corresponds to the ^{194}Hg isotope abundance of the order of 10^{-18}.

In November 1984 we took away the mercury in order to eliminate the 2043.7 keV peak, since it is very close to the energy of the $0^+ \to 0^+$ neutrino-less double beta decay of ^{76}Ge. In later measurements lines of ^{194}Hg disappeared perfectly..

However, two problems still remain.

(1) Where ^{194}Hg isotope comes from ?

Since the half-life of ^{194}Hg (= 260 years) is so short compared with the age of the earth, it leads us to the idea that the cosmic ray, perhaps neutrons induced by cosmic ray, furnishes the radioactive isotope ^{194}Hg day after day. For example, the reaction $^{196}Hg(n,3n)^{194}Hg$ may be possible.

(2) Why no such peaks in the measurements by Milano group ?

Though Milano group also uses mercury shield inside the detector system, the spectra are free from ^{194}Hg lines. In fact Bellotti suggested in Neutrino '84 conference that the line at 2044 keV would be likely due to a radioactive contamination of copper or of lead(2). It would be likely that the mercury used by Milano group would contain much less amount of ^{194}Hg compared with that of us, since the production of the ^{194}Hg by cosmic neutrons would depend on the location of the mercury ore.

Figure Caption

Fig. A1 The decay scheme of ^{194}Hg and its daughter nuclei.

References

1. C.M. Lederer and V.S. Shirley, Table of Isotopes (7th. ed.), John Wiley and Sons, (1978)

2. E. Bellotti, Proc. 11th. Int. Conf. Neutrino Physics and

Astrophysics (Neutrino'84), Dortmunt, June 1984, edited by K. Kleinknecht and E.A. Paschos, World Scioentific, (1984)p.171

γ-ray Energy	Intensity per Decay A (%)	Escape from Hg layer B (%)	Passing through NaI C (%)	Ge Peak Effi. D (%)	Expected Counts of peak (Arbitrary) A・B・C・D	Observed Counts of peak at Osaka (10^{-3} / Hour)	Observed Counts of peak at Kamioka (10^{-3} / Hour)
1468.9 keV	10.6	40	27	14.5	166	31	22
1592.4 keV 1593.5 keV 1595.8 keV	5.97	41	28	13.6	94	12	22
1885.9 keV 1887.0 keV	5.4	45	30	12.1	87	16	18
1924.1 keV	3.5	45	31	11.9	58	5.0	6.8
2043.7 keV	6.3	46	32	11.4	106	13	9.3

Table A1

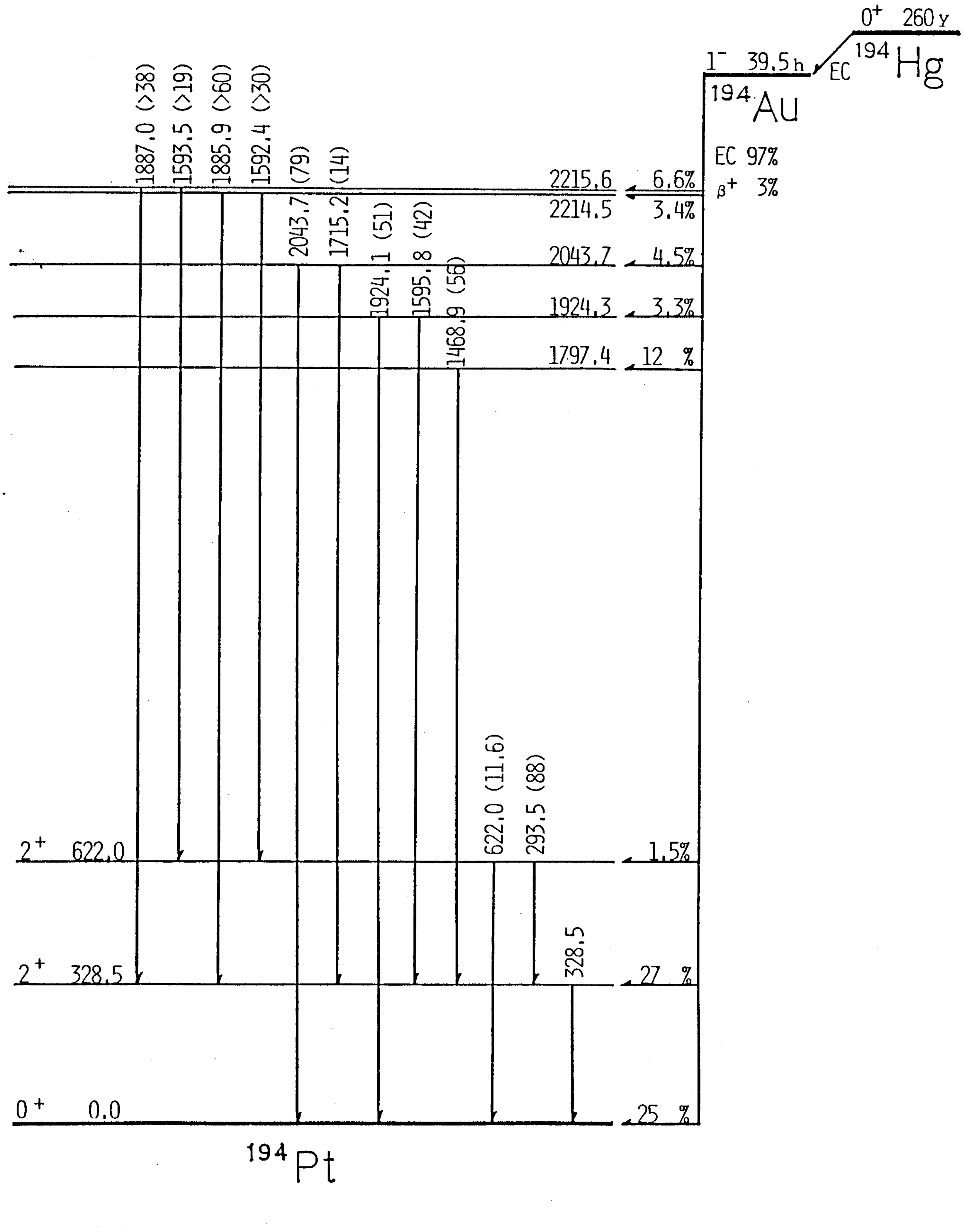

0+ 260 y
194Hg
EC
1− 39.5 h
194Au
EC 97%
β+ 3%
1887.0 (>38)
1593.5 (>19)
1885.9 (>60)
1592.4 (>30)
2043.7 (79)
1715.2 (14)
1924.1 (51)
1595.8 (42)
1468.9 (56)
622.0 (11.6)
293.5 (88)
328.5
2215.6 6.6%
2214.5 3.4%
2043.7 4.5%
1924.3 3.3%
1797.4 12 %
2+ 622.0 1.5%
2+ 328.5 27 %
0+ 0.0 25 %
194Pt

Fig. A1

APPENDIX B Evaluation of peak counts hidden in continuum backgrounc

Statistics of the present rare decay data with the small number of counts is expressed by the Poisson distribution. (If the number of counts is large, one may use the simple Gaussian distribution instead as used in most of nuclear phyics experiments.)

The Poisson distribution is expressed by only one parameter μ.

$$f_{\mu}(n) \equiv \frac{\mu^n}{n!}\cdot e^{-\mu} \qquad (1)$$

where μ is the mean value of the parent distribution and n is the positive integer or zero. This is normalized as

$$\sum_{n=0}^{\infty} f_{\mu}(n) = \sum_{n=0}^{\infty} \frac{\mu^n}{n!}\cdot e^{-\mu} = 1 \qquad (2)$$

The observed counts Y at the peak region is considered to be the sum of the true peak counts Y_T and the background counts in the region of the peak Y_{BG}.

$$Y = Y_T + Y_{BG} \qquad (3)$$

Note that Y, Y_T and Y_{BG} are positive integer or zero. The statistics for both the Y_T and Y_{BG} are given by the Poissson distributions.

$$f_{tr}(Y_T) = \frac{tr^{Y_T}}{Y_T!}\cdot e^{-tr} \qquad (4)$$

$$f_{bg}(Y_{BG}) = \frac{bg^{Y_{BG}}}{Y_{BG}!}\cdot e^{-bg} \qquad (5)$$

where tr is the average value of the true peak counts, and bg is that of observed background counts.

Actually the total counts Y and the average background counts bg can be determined by an observation. Assuming the expected peak counts is t, the probability that the sum of two Poisson distributions (t and bg) is proportional to K(t) defined as follows.

$$K(t) \equiv f_t(0)\cdot f_{bg}(Y) + f_t(1)\cdot f_{bg}(Y-1) + \ldots + f_t(Y)\cdot f_{bg}(0)$$

$$= \sum_{n=0}^{Y} f_t(n)\cdot f_{bg}(Y-n) \qquad (6)$$

The normalized representation is

$$P(t) \equiv \frac{K(t)}{\int_0^\infty K(x)dx}$$

$$= \frac{\sum_{n=0}^{Y} f_t(n)\cdot f_{bg}(Y-n)}{\sum_{n=0}^{Y} f_{bg}(n)} \qquad (7)$$

Note that $\int_0^\infty P(x)dx = 1$. The probability that the peak counts is an interval between a and b is written as $\int_a^b P(x)dx$.

The probability Q(t) that the peak (true) counts is less than t is

$$Q(t) \equiv \int_0^t P(x)dx$$

$$= \frac{1}{\sum_{n=0}^{Y} f_{bg}(n)} \cdot \sum_{n=0}^{Y} f_{bg}(Y-n)\cdot\left(1-e^{-t}\cdot\sum_{m=0}^{n}\frac{t^m}{m!}\right) \qquad (8)$$

The value 't' at which Q(t) becomes 0.68 is considered to be the upper limit on the hidden peak counts in continuum backgrounds at the 68 % confidenceal level.

Here gives the example to deduce the hidden peak counts from the spectrum of the $0^+\to 0^+$ transition for the RUN 3 measurement. (See Fig. 3-2(c)) Considering the energy resolution of the Ge detector at the $0^+\to 0^+$ transition energy, the observation is done in the window of 5 channels (3.85 keV). Since small peaks are found at the higher energy part of the spectrum, such region is not taken into account for the average of the background counts. The observed background counts in that region is averaged to be 3.33 counts/ch. According to the notation used above, Y = 15 and bg = 16.7.

From the Eq. (7) and Eq. (8) with observed values of Y and bg, one can calculate the probabilities P(t) and Q(t). The graph of Q(t) tells that the hidden peak counts in the window is less than 3.9 counts on the 68 % confidence level. Taking into account the probability that the peak counts fall into the window, one can estimate the counts to be 4.5 counts on the 68 % confidence level.

It is interesting to compare the possible peak counts calculated by using the Poisson distribution and with that by using the Gauss distribution. On the basis of the Gauss distribution the possible peak counts is

$$t = \frac{\sqrt{N_i(BG)\cdot\Delta E\cdot \mathrm{time}}}{0.763} \qquad (9)$$

where $N_i(BG)$, ΔE,time are the observed background rate, the energy resolution, and the measured period. A value of 0.763 means the probability that the peak counts fall into the ΔE (energy resolution) window. They are listed in Table B1. They agree well with each other.

References

for general discussions

Data Reduction and Error Analysis for the Physical Science, edited by P.R. Bevington, Mcgraw-Hill(1969)

RUN	N_i(BG) counts/keV hr	Δ E keV	time hours	T(Gauss) counts	Y_t(Poisson) counts
RUN2 $0^+ \rightarrow 0^+$	6.5×10^{-4}	3.0	1600	2.3	3.2
RUN2 $0^+ \rightarrow 2^+$	1.6×10^{-4}	2.5	1600	1.0	1.2
RUN3 $0^+ \rightarrow 0^+$	6.2×10^{-4}	3.0	6977	4.7	4.5
RUN3 $0^+ \rightarrow 2^+$	2.7×10^{-4}	2.5	6977	2.8	2.5

Table B1

APPENDIX C The electronics and the data-taking for the ELEGANTS

1. Electronics

The detectors used for the ELEGANTS are the pure Ge, the 4π-NaI counter divided into six segments and six plastic scintillators. The electronics for the ELEGANTS was constructed to be triggered by all signals beyond 40 keV from the Ge detector.

The energy of the Ge is measured with two lines. One is for the energy region of 0 ∿ 3 MeV and fed into the spectroscopic amplifier (ORTEC 571) with shaping time of 10 μsec.. The energy threshold is about 40 keV. Another is for the energy up to 20 MeV and connected to CAMAC ADC (LeCroy 2259). Typical trigger rates of the Ge are 1.3 per sec. at the sea-level Osaka laboratory and 0.06 per sec. at the Kamioka underground laboratory, respectively.

The energies of six NaI segments are also connected to the CAMAC ADC. The gate signals of 500 nsec. duration for the NaI energies are generated by the trigger signal. The energy range for the NaI detector is 0 ∿ 3 MeV. Timing signals are 'OR'ed together and are used as the start signal of the Time-to-Amplitude converter (TAC) with a 20 μsec. range. The stop signal is obtained from the Ge detector. Threshold energies of the NaI segments are 40 ∿ 80 keV. The sum of the signals from NaI segments shows a counting rate of about 50 per sec. at the sea-level Osaka laboratory, while at the Kamioka underground laboratory it is 20 ∿ 30 per sec..

The plastic scintillators are used for only timing devices. Six timing signals are summed and are connected to the start of another TAC, just same as the case of the NaI signals. Summed counting rate is 150 per sec. at the sea-level Osaka.

The block diagram of the electronics for the ELEGANTS is given in Fig. 1.

2. Data-taking by a mini-computer

The data-taking system for the ELEGANTS had been developed in 1983. The mini-computer used is PDP11/10. The hardware configuration is given in Fig. 2. As is shown in it, it is very small system for recent day's experiments. RT11SJ monitor is used for the operating system (OS), since it requires only a small memory size.

All the detector signals are fed into CAMAC. The computer takes these data through CAMAC, and records them on a magnetic tape in list mode together with the date and time of every event.

At the sea-levl Osaka the trigger rate is 1.3 per sec. as noted above, and about 10 individual signals are managed for an every trigger. This counting rate is sufficientlly low for even such an old computer. For the measurements of high counting rate with γ-ray sources, the trigger signal is processed by means of the interrupt technique for the real-time response.

Since one measurement continues for several days, simple spectra of every detectors should be monitored online on the graphic terminal. Otherwise one would not find troubles, such as a cable disconnection, until the offline analysis of the magnetic tapes. We have monitored histgrams for all detectors. The resident area for the histgrams in the RAM memory is about 20 kB, which is almost a half of the memory of our computer.

3 Applications of software products

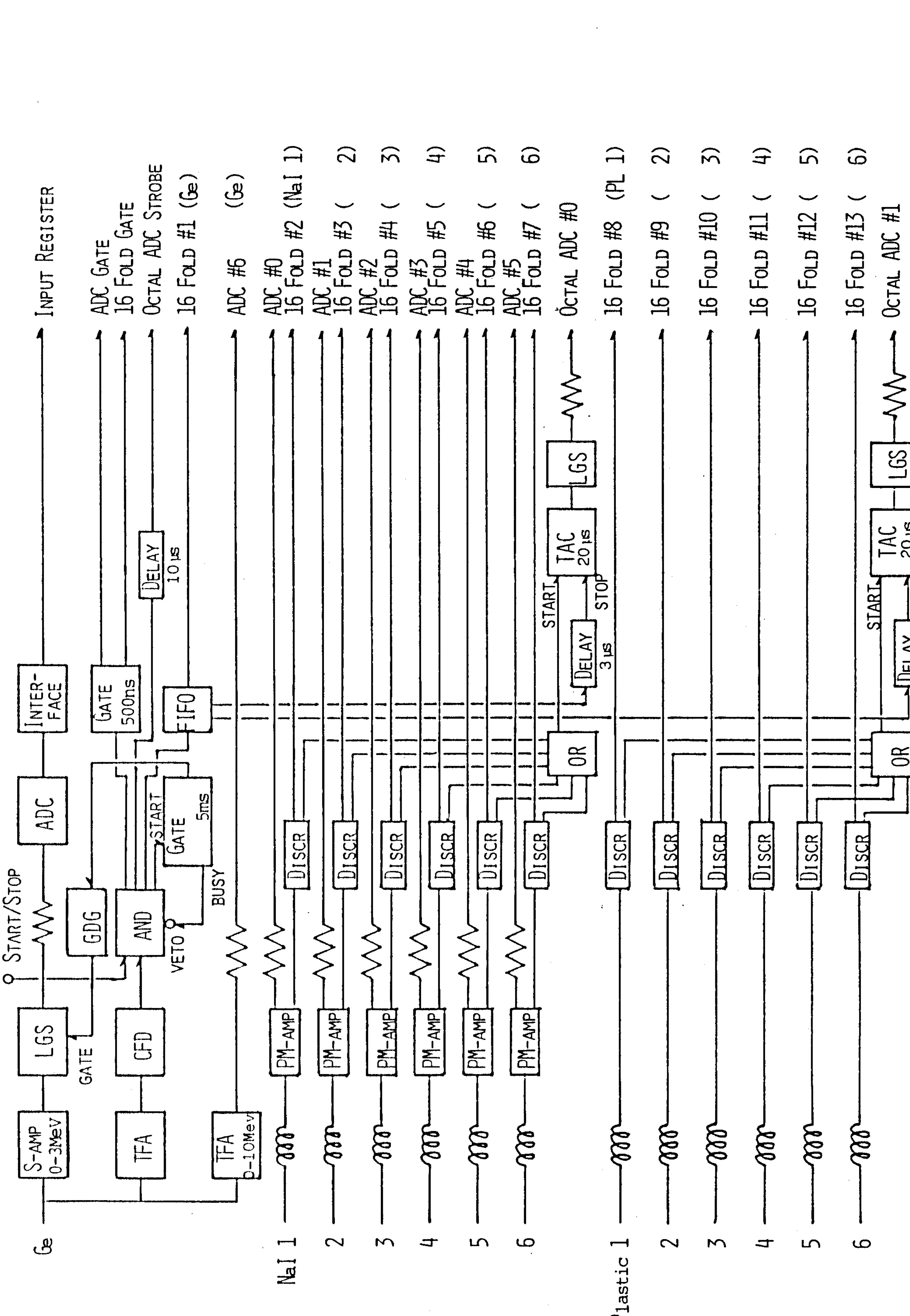
During the developement of this data-taking program, some of the basic and useful routines are moduled into subroutine forms. For example, the online display of the histgrams, the magnetic tape control, the graphic tools ... etc..

The data-taking program for the 11 stacks of Si detectors has been prepared recently by utilizing fully these subroutines. It will be used for the experiment of the ^{100}Mo ββ decay. This experiment will start soon in early 1986 at the Kamioka underground laboratory. They are also used by the data-taking system for the test experiment of the ^{130}Te ββ decay, which uses 12 plastic scintillators surrounded by 6 NaI detectors and plastic veto counters for cosmic-rays. It has beeen operated at the sea-level Osaka laboratory since December 1985 with LSI11/2 mini-computer.

Figure Captions

Fig. C1 The block diagram of the electronics for the ELEGANTS at the sea-level laboratory in Osaka. The part of modules to accept tl signals from plastic scintillators are removed at the Kamioka underground labo..

Fig. C2 The hardware configuration of the PDP11/10 mini-computer



Input Register
ADC Gate
16 Fold Gate
Octal ADC Strobe
16 Fold #1 (Ge)
ADC #6 (Ge)
ADC #0
16 Fold #2 (NaI 1)
ADC #1
16 Fold #3 (2)
ADC #2
16 Fold #4 (3)
ADC #3
16 Fold #5 (4)
ADC #4
16 Fold #6 (5)
ADC #5
16 Fold #7 (6)
Octal ADC #0
16 Fold #8 (PL 1)
16 Fold #9 (2)
16 Fold #10 (3)
16 Fold #11 (4)
16 Fold #12 (5)
16 Fold #13 (6)
Octal ADC #1
Ge
S-AMP 0-3MeV
LGS
Start/Stop
ADC
Inter-face
TFA
CFD
AND
GDG
GATE
VETO
BUSY
START
Gate 5ms
Gate 500ns
FIFO
Delay 10 µs
TFA 0-10Mev
NaI 1
2
3
4
5
6
PM-AMP
Discr
OR
TAC 20 µs
START
STOP
Delay 3 µs
LGS
Plastic 1

Fig. C1

app. C 4

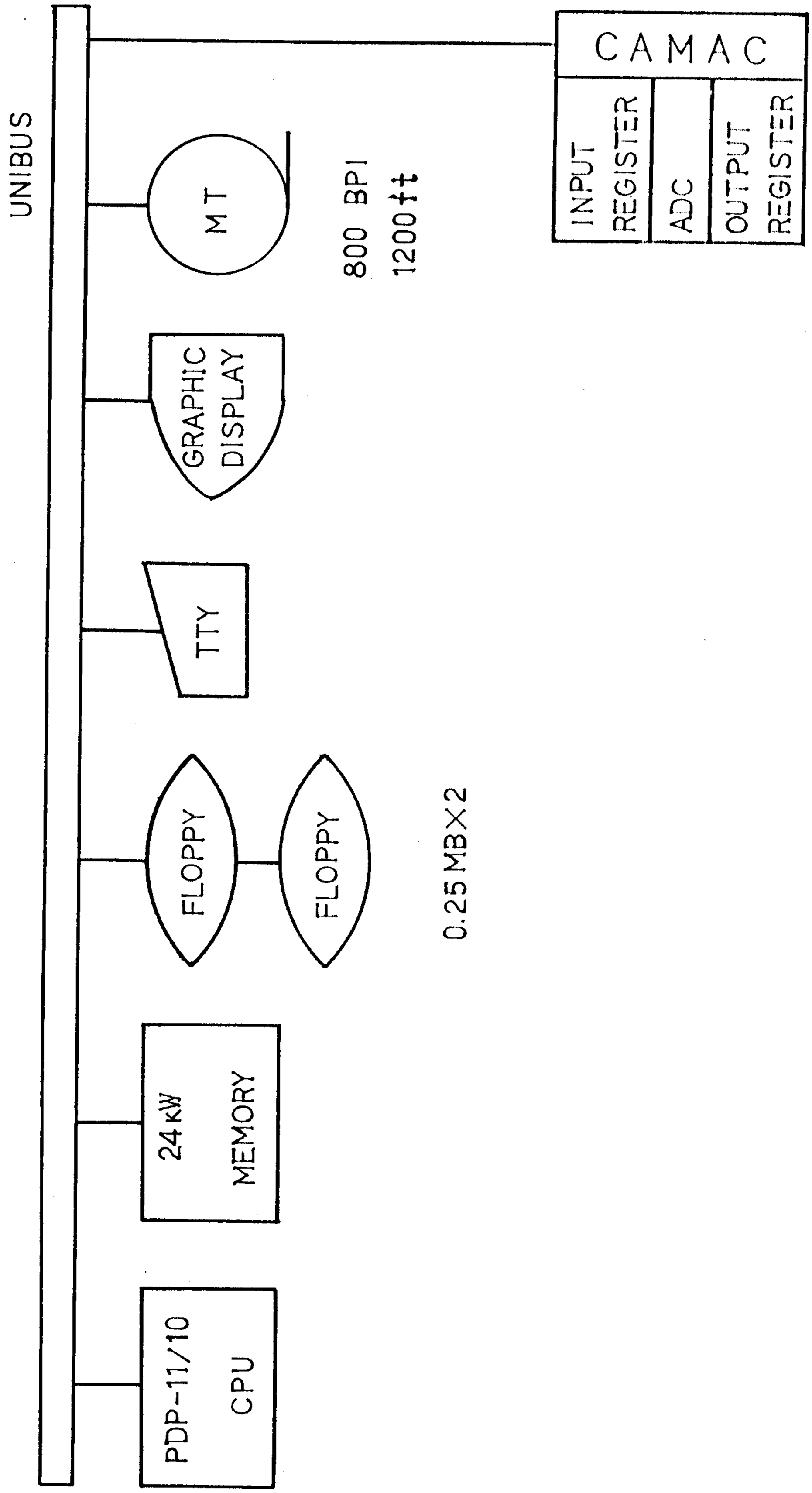

UNIBUS
CAMAC
INPUT REGISTER
ADC
OUTPUT REGISTER
MT
800 BPI
1200 ft
GRAPHIC DISPLAY
TTY
FLOPPY
FLOPPY
0.25 MB×2
24 kW MEMORY
PDP-11/10 CPU

Fig. C2

FIGURE CAPTIONS

Fig. 1-1 Decay schemes of ^{76}Ge and ^{48}Ca as typical source nuclei for double beta decays

Fig. 1-2 Schemes of the mechanisms for the neutrino-less(0ν) double beta decay. (a) two nucleon (2n) process, (b) Δ^{++} process, (c) Δ^{-} process

Fig. 2-1 (a) Schematic arrangement of the Ge counter with an internal RI(RII) of ^{208}Tl, being surrounded by a 4π γ-counter consisting of four NaI segments. γ_3^c is the Compton scattered γ_3. (b) Major γ-decay scheme of ^{208}Tl.

Fig. 2-2 Schematic views of the ELEGANTS. Ge: 171 cc Ge detector, NaI: 4π-NaI of 10"$\phi\times$12" and 8"$\phi\times$3", PL: 2π-plastic scintillators, Hg: 27 mm pure mercury, Cu: 15 cm OFHC copper, Pb: 15 cm lead, Cd: 0.5 mm Cd sheet, PA: 1 m thick paraffine blocks, D: liquid N_2 dewar A: acryl plate box for air-tight

(a) Side view of the ELEGANTS at the sea-level Osaka Univ.. Plastic scintillators with 2π-geometry are used to identify charged cosmic-rays. Paraffine blocks and Cd sheet are mounted on the top of the ELEGANTS.

(b) Side view of the ELEGANTS at the Kamioka underground laboratory. N_2 gas evaporated from the liquid N_2 coolant is fed into the center of the ELEGANTS. Five acryl plates provide a complete air-tight room for the whole detector system.

(c) Cross sectional view of the Ge and NaI detectors.

Fig. 2-3 The background spectra of 3"$\phi\times$3" NaI without any shields. (a) measured at sea-level Osaka for 25.00 hours, (b) measured at Kamioka for 1.944 hours

Fig. 2-4(a) Background spectra of the Ge detector obtained at sea-level Osaka. B: without any shields for 2500 seconds, S: in the ELEGANTS measured for 1055 hours, A: in the ELEGANTS anticoincidenced with the 4π-NaI and the 2π-plastic scintillators measured for 1055 hours, C: in the ELEGANTS coincidenced with the $2^+\rightarrow0^+$ 559 keV γ-ray signal from 4π-NaI detector. Coincidence energy window is 70 keV.

Fig. 2-4(b) Background spectra above 3 MeV measured at sea-level Osaka for 1055 hours. S for singles and A for anticoincidence with any NaI detectors. Counts per energy bin of every 200 keV (100 keV below 3 MeV) are shown with statistic error. Zero count is not shown.

Fig. 2-5(a) The background spectra of the Ge detector obtained at the Kamioka underground laboratory. B: without any shields for 15.27 hours, S: in the ELEGANTS measured for 144.63 hours, G: in the ELEGANTS with the introduction of nitrogen gas, measured for 2082 hours, C: in the ELEGANTS coincidenced with the $2^+\rightarrow0^+$ 559 keV γ-ray signal from 4π-NaI detector measured for 2082 hours. The coincidence energy window is 100 keV.

Fig. 2-5(b) Background spectra above 3 MeV measured at the Kamioka underground laboratory for 5371 hours. G for singles with N_2 gas circulation and A for anticoincidence. Counts per energy bin of every 200 keV (100 keV below 3 MeV) are shown with statistic error. Zero count is not shown.

Fig. 2-6 Multiplicity distribution for signals from six segment NaI detectors gated by the Ge detector. $F_A(M)$ and $F_N(M)$ are observed distributions with and without signals from the active (plastic) shield, respectively. $f_C(M)$ and $f_R(M)$ are distributions for charged cosmic rays and others, respectively.

Fig. 2-7 The energy spectra of the Ge from 100 to 225 keV. The upper is the measurement at the sea-level Osaka for 1055 hours. The lower is at the Kamioka underground labo. for 2082 hours. The peaks at the energies of 139.7 keV and 198.6 keV are the γ-ray from the decay of ^{75}Ge and its isomer. The peaks appeared at 186 keV in both spectra are due to the decay of ^{226}Ra.

Fig. 2-8 Normalized intensities of peaks vs. energy for ^{238}U decay chain. Five individual results are shown.

(a) Results at the sea-level laboratory of Osaka Univ.. Osaka-B: at sea-level Osaka without any shields (mode B), and Osaka-S: at sea-level Osaka in the ELEGANTS (mode S), (b) Results at the Kamioka undeground laboratory, Kamioka-B: at Kamioka underground without any shield (mode B), Kamioka-S: at Kamioka underground in the ELEGANTS without N_2 gas circulation (mode S), and Kamioka-G: at Kamioka underground in the ELEGANTS with N_2 gas circulation (mode G)

Fig. 2-9 Observed counts of β-rays from ^{214}Pb in coincidence with the NaI signals in the given energy window. The error bar contains the error due to subtraction of the continuum and the statistic error. (a) Counts of 295.21 keV γ-ray. The endpoint energy of accompanying β-ray is 729 keV. (b) Counts of 351.92 keV γ-ray. The endpoint energy is 672 keV.

Fig. 3-1 The observed energy resolutions for the typical γ-ray peaks. These are the results of the RUN 3 measurement, which was operated at the Kamioka underground labo. for 6977 hours.

Fig. 3-2 The enlarged spectra around the enrgies of our interest.

(a) The specta of the RUN 1 at the sea-leval Osaka for 2115 hours. The peak at the enrgy of 2043.7 keV for the $0^+ \to 0^+$ is due to the decay of ^{194}Hg.

(b) The spectra of RUN 2 at the Kamioka underground labo. for 1600 hours. The peak for the $0^+ \to 0^+$ is also due to the ^{194}Hg.

(c) The spectra of RUN 3 at tha Kamioka for 6977 hours. The mercury shield are removed. The small peak at 2054 keV may be due to the radioactivity.

Fig. 3-3 The plots of the present upper bounds for the neutrino mass ($x = \langle m_\nu \rangle / m_e$) and the right-handed coupling term in weak interaction (y, see Eq. 1-6). Three plots correspond to three matrix elements used. K is the matrix element calculated by Doi et. al. (Doi84), H is by Haxton (Haxton84), and G is by Grotz (Grotz83).

Fig. 4-1 Si detectors and Mo foils set inside the well of the 4π-NaI counters. The arrangement is the same as in Fig. 2(c) except the Ge detector, which is replaced by Si detector array. NaI: NaI detectors, Si: Si detectors, M: ^{100}Mo foils, Hg: pure mercury, C: cold finger

Transion	A	Z	Isotopic abundance (%)	Transition energy (MeV)	Intermediate transition energy (A,Z) -(A,Z+1)
Ca-Ti	46	20	0.0033	0.985±0.009	-1.382 ±0.011
Ca-Ti	48	20	0.185	4.267±0.009	+0.289 ±0.012
Zn-Ge	70	30	0.62	1.008±0.006	-0.653 ±0.009
Ge-Se	76	32	7.67	2.041±0.001	-0.923 ±0.004
Se-Kr	80	34	49.82	0.138±0.007	-1.871 ±0.005
Se-Kr	82	34	9.19	3.003±0.008	-0.089 ±0.008
Kr-Sr	86	36	17.37	1.240±0.006	-0.0537±0.008
Zr-Mo	94	40	2.80	1.230±0.005	-0.921 ±0.014
Zr-Mo	96	40	17.40	3.364±0.005	+0.215 ±0.025
Mo-Ru	100	42	9.62	3.034±0.006	-0.335 ±0.060
Ru-Pd	104	44	18.5	1.321±0.012	-1.145 ±0.008
Pd-Cd	110	46	12.7	2.004±0.013	-0.868 ±0.015
Cd-Sn	114	48	28.86	0.547±0.008	-1.439 ±0.008
Cd-Sn	116	48	7.58	2.811±0.006	-0.517 ±0.024
Sn-Te	122	50	4.71	0.349±0.008	-1.622 ±0.008
Sn-Te	124	50	5.98	2.263±0.007	-0.653 ±0.008
Te-Xe	128	52	31.79	0.872±0.007	-1.268 ±0.010
Te-Xe	130	52	34.49	2.543±0.008	-0.407 ±0.030
Xe-Ba	134	54	10.44	0.731±0.039	-1.328 ±0.039
Xe-Ba	136	54	8.87	2.718±0.080	-0.112 ±0.080
Ce-Md	142	58	11.07	1.379±0.049	-0.777 ±0.050
Nd-Sm	148	60	5.71	1.936±0.021	-0.514 ±0.030
Nd-Sm	150	60	5.60	3.390±0.020	-0.036 ±0.062
Sm-Gd	154	62	22.61	1.260±0.022	-0.718 ±0.024
Gd-Dy	160	64	21.75	1.782±0.030	-0.029 ±0.030
U-Pu	238	92	99.275	1.173±0.034	-0.117 ±0.031

Table 1-1

Table of isotopes for which double beta decay can occur. Single beta decay is forbidden from the Q value, or storongly inhibited because of the large difference of spin and parity. Most of values are quoted from the reference (Fiorini72b).

Mechansim / Transition	$(\beta\beta)_{2\nu}$ mode		$(\beta\beta)_{0\nu}$ mode			
			Neutrino Mass Part		Right-handed Current Part	
	2n	N^*	2n	N^*	2n	N^*
$0^+ \to 0^+$	○	×	○	×	○	×
$0^+ \to 1^+$	o	o	×	×	○	○
$0^+ \to 2'^+$	o	o	×	×	○	○

Table 1-2

Selection rules for the $\beta\beta_{2\nu}$ mode and $\beta\beta_{0\nu}$ mode. The circle(cross) indicates the allowed (not allowed) transition. The small circle in the $\beta\beta_{2\nu}$ mode means the suppression of this transition. The table is quoted from Doi83a.

	$T_{1/2}^{0\nu+2\nu}$ (years)	geo. exp.	$T_{1/2}^{0\nu}$ (years)	geo. exp.	$T_{1/2}$ theory (years)
$^{130}Te \rightarrow ^{130}Xe$	$(2.55\pm0.2)\times10^{21}$		$> 2.15\times10^{21}$		1.7×10^{19}
$^{128}Te \rightarrow ^{128}Xe$	$> 8\times10^{24}$		$> 8\times10^{24}$		9×10^{22}
$^{82}Se \rightarrow ^{82}Kr$	$(1.7\pm0.3)\times10^{20}$		$> 1.1\times10^{20}$		2.6×10^{19}

Table 1-3 Experimental results of geochemical ββ decay experiments. The halflife is accounted for the sum of both the 0ν and the 2ν mode process. The theoretical predictions by Haxton (Haxton84) are also given. (Quoted from Kirsten84a-b)

Group	Milano	Guelph Downsview Kingston	CALTECH
Place	Mont Blanc 4200 mwe	Salt-mine 330 m depth	Caltech Sea-level
Active device	none	Plastic	4π-Plastic
Ge volume (Fidutial)	125cc & 153cc (115cc & 145cc)	208 cc (194 cc)	(90 cc)
Time (hours)	14500 & 4741	2363	2600
$T_{1/2}$ ($\times 10^{22}$ years)	10 & 7 (Total 12)	3.2	1.7
References	Bellotti84a	Simpson84	Forster84

Table 1-4(a) The experimental halflife limits on the $0\nu\beta\beta$ decay of the ^{76}Ge $0^+ \to 0^+$ transition obtained so for. The Milano group and the UCSB/LBL group have two diodes. All the halflife limits are calculated at the 68 % C.L., except for the CALTECH group with the 90 % C.L..

Group	Santa-Barbara Berkeley (UCSB/LBL)	Battle South-Carolina (PNL/USC)	Osaka
Place	Berkeley low-level lab.	Homestake mine 4084 mwe	Kamioka 2700 mwe
Active device	4π-NaI	4π-plastic	4π-NaI
Ge volume (Fidutial)	178cc & 158c (159cc & 140cc)	135 cc (125 cc)	171 cc (164 cc)
Time (hours)	1618	3763	8577
$T_{1/2}$ ($\times 10^{22}$ years)	5	11.6	7.4
References	Caldwell85	Avignon85	This thesis

Table 1-4(a) (continued)

Group	Milano	Guelph Downsview Kingston	Bordeaux Zaragona	Osaka
Place	Mont Blanc 4200 mwe	Salt-mine 330 m depth	Sea-level	Kamioka mine 2700 mwe
Active device	none	Plastic	NaI coin.	4π-NaI
Ge volume (Fidutial)	125cc & 153cc (115cc & 145cc)	208 cc (194 cc)	$\sim$ 100 cc	171 cc (164 cc)
Time (hours)	14500 & 4741	2363	1360	8577
$T_{1/2}$ ($\times 10^{22}$ years)	1.6 & 1.6 (Total 2.2)	1.6	0.2	5.6
References	Bellotti84b	Simpson84	Leccia83	This thesis

Table 1-4(b) The experimental halflife limits on the $0\nu\beta\beta$ decay of the ^{76}Ge $0^+ \to 2^+$ transition. All the halflife limits are calculated at the 68 % C.L..

	Guelph Downsview Kingston		CALTECH		Battelle South-Carolina (PNL/USC)	
	PRESENT	FUTURE	PRESENT	FUTURE	PRESENT	FUTURE
Experimental Area	Salt mine 330 m depth	Salt mine 330 m depth	CALTECH Sea-leval	Gothard tunnel	Sea-level	Homestake mine 4084 mwe
Ge crystal volume	208 cc	3 × 200 cc	90 cc	total ~ 1000 cc	125 cc	14 crystal total 1440 cc

Table 1-5

The present status and future plans of the ^{76}Ge $\beta\beta$ experimental groups.

	Santa-Barbara Berkeley (UCSB/LBL)		Bordeaux Zaragona		Osaka	
	PRESENT	FUTURE	PRESENT	FUTURE	PRESENT	FUTURE
Experimental Area	LBL Low-level Facility	Oroville Dam 200 m depth	Sea-leval	Frejus tunnel	Kamioka mine 2700 mwe	?
Ge crystal volume	178 cc + 154 cc	8 × 200 cc	90 cc	4 × 100 cc	171 cc	?

Table 1-5 (continued)

Sample	^{232}Th	^{238}U	^{60}Co	^{40}K	^{137}Cs
Voltage divider	< 5(3)	23(8)	4(2)	80(50)	< 2.2
Light shield	< 0.8	3.6(2.5)	1.1(7)	< 14	0.9(8)
Prop. thermo.	11(6)	120(40)	< 6	< 90	14(6)
Black epoxy	7(5)	27(13)	12(5)	< 80	8(5)
Hardener	< 4.3	< 10	< 6	< 150	< 5
Thermogel(#13)	< 4.3	39(16)	< 3	< 80	7(5)
Thermogel(#12)	< 6	< 12	3.5(3.0)	< 70	< 3
OFHC copper(#1)	< 0.2	< 0.5	< 0.2	< 4	< 0.24
Teflon refl.	< 0.3	< 2	< 0.9	< 14	< 0.7
Al_2O_3 refl.	5(1)	6(2)	< 0.6	< 11	0.63(55)
MgO refl.	< 0.7	< 4	0.7(6)	< 14	1.4(8)
OFHC copper(#2)	< 0.1	< 0.3	< 0.08	< 2.3	< 0.11
Al piece	0.7(5)	< 1	1.3(5)	< 10	1.9(1.6)

Table 2-1 Radioactive contaminations in various materials used for the ELEGANTS. Values in the table are given in the unit 10^{-2} dpm per gram. The bracket indicates an error.

Osaka Univ. Sea-level Labo.

Chain	Source	E(keV)	mode B	mode S	mode A
^{238}U	^{226}Ra	186†	230(60)	0.43(5)	0.49(3)
	^{214}Pb	352	1220(40)	3.43(7)	3.23(6)
	^{214}Bi	609	1370(40)	2.80(6)	0.52(3)
	^{234m}Pa	1001	23(12)	0.04(2)	0.04(1)
^{232}Th	^{212}Pb	239	1630(60)	1.71(5)	1.77(4)
	^{208}Tl	583	940(30)	0.64(4)	0.16(2)
	^{228}Ac	911	750(30)	0.63(3)	0.49(2)
	^{208}Tl	2614	860(30)	0.55(3)	0.21(2)
^{40}K	^{40}K	1460	8600(80)	3.99(6)	3.97(6)
continuum		500- 600	16250	163	2.5
component		1000-1100	7210	50.8	0.97
		1500-1600	984	26.2	0.43
		2000-2100	504	16.6	0.15
		2500-2600	133	11.7	0.09

† together with the 185.72 keV γ-ray from ^{235}U.

Table 2-2(a) Counting rates of peaks and continuum components in various modes of the ELEGANTS at the sea-level laboratory of Osaka Univ.. The values in the table are given in counts per hour for peaks, and in counts per hour per 100 keV for continuum components. The bracket indicates an error. The exposure period of the mode B is 1.364 hours. The measurements of the mode S and A are for 1055 hours.

Kamioka Underground Laboratory

Chain	Source	E(keV)	mode B	mode S	mode G	mode A
^{238}U	^{226}Ra	186†		0.5(1)	0.77(3)	0.75(2)
	^{214}Pb	352	17200(100)	50.5(6)	4.24(5)	3.91(5)
	^{214}Bi	609	15320(40)	32.4(5)	2.71(4)	0.57(2)
	^{234m}Pa	1001	12(7)	0.055(53)	0.039(6)	0.029(8)
^{232}Th	^{212}Pb	239		1.6(2)	1.94(4)	1.92(4)
	^{208}Tl	583	1290(20)	0.51(9)	0.52(2)	0.16(1)
	^{228}Ac	911	960(20)	0.6(1)	0.63(2)	0.49(2)
	^{208}Tl	2614	1090(10)	0.50(6)	0.45(2)	0.22(1)
^{40}K	^{40}K	1460	7550(20)	3.9(2)	3.97(4)	3.94(4)
continuum		500- 600	26300	47.7	11.3	1.60
component		1000-1100	10650	19.9	5.0	0.65
		1500-1600	3150	10.0	1.3	0.22
		2000-2100	951	1.9	0.41	0.06
		2500-2600	131	0.2	0.10	0.004

† together with the 185.72 keV γ-ray from ^{235}U.

Table 2-2(b) Counting rates of peaks and continuum components in various modes of the ELEGANTS at the Kamioka underground laboratory. The values in the table are given in counts per hour for peaks, in counts per hour per 100 keV for continuum components. The bracket indicates an error. The exposure period of the mode B is 15.27 hours at Kamioka. The measurements of the the mode G and A are for 2082 hours. The mode S run is for 144.63 hours.

Group	Milano	Guelph Downsview Kingston	CALTECH	Santa-Barbara Berkeley
Place	Mont Blanc 5000 & 4200 mwe	Salt-mine 330 m depth	Caltech Sea-level	Berkeley low-level lab.
Active device	none	Plastic	4π-Plastic	4π-NaI
S_0 ($\times 10^{22}$)	6.1 & 15.7	6.4	4.0	8.6 & 9.2 (12.5)
N_0 ($\times 10^{22}$)	41.0 & 48.5	68.1	29.5	58.3 & 51.7
N_0(BG) (counts/keV•y)	14.9 & 3.2	37.2	18.4	11.4 & 7.9
ΔE (keV)	< 3 & < 3	3	3.0	4
References	Bellotti84b Liguori83	Simpson84 Jagem85	Forster84	Caldwell85

Table 2-3(a) Sensitivities (S_0) of various detectors used for the $0\nu\beta\beta$ decay of the ^{76}Ge $0^+\rightarrow 0^+$ transition. The Milano group and the Santa Barbara-Berkeley group have two diodes, and two values for each diode are given in the table. The S_0 given in bracket is the sum value of two diodes. In the table, N_0 is the number of ^{76}Ge nuclei, N_0(BG) is the background rate at the energy of the $0^+\rightarrow 0^+$ transition, and ΔE is the energy resolution at the energy of interest, respectively.

Group	Battle South-Carol. 1	Battle South-Carol. 2	Osaka 1	Osaka 2
Place	Sea-level	Homestake mine 4084 mwe	Osaka Sea-level	Kamioka 2700 mwe
Active device	3π-NaI	4π-Plastic	4π-NaI 2π-Plastic	4π-NaI
S_0 ($\times 10^{22}$)	2.8	16.5	7.0	13.5
N_0 ($\times 10^{22}$)	43.2	42.6	56.0	56.0
N_0(BG) (counts/keV•Y)	70.1	1.8	18.1	5.7
ΔE (keV)	3.4	3.7	3.0	3.0
References	Avignon83	Avignon85 Brodzinski85	Ejiri84	Ejiri85a-b Ejiri86

Table 2-3(a) (continued)

Group	Milano	Bordeaux	Osaka 1	Osaka 2
Place	Mont Blanc 5000 & 4200 mwe	Sea-level	Osaka Sea-level	Kamioka 2700 mwe
Active device	none	NaI coin.	4π-NaI 2π-Plastic	4π-NaI
S_1 ($\times 10^{22}$)	2.9 & 5.9	0.77	4.6	7.9
N_0 ($\times 10^{22}$)	41.0 & 48.5	32.8	56.0	56.0
N_1(BG) (counts/keV·y)	35.1 & 12.3	45.7	6.3	2.3
ΔE (keV)	2.7 & 2.7	2.3	2.7	2.5
k_1	0.70	0.24	0.34	0.34
Reference	Bellotti84 Liguori83	Leccia83	Ejiri84	Ejiri85a-b Ejiri86 Kamikubota86

Table 2-3(b) Sensitivities (S_1) of various detectors used for the $0\nu\beta\beta$ decay of the ^{76}Ge $0^+ \rightarrow 2^+$ transition. The groups of Guelph-Downsview-Kingston, Santa-Barbara-Berkeley and Battle-South Carolina are not listed in the table, since parameter(s) used to deduce the sensitivities are not given in their references. In the table, N_0 is the number of ^{76}Ge nuclei, N_1(BG) is the background rate, ΔE is the energy resolution at the energy of interest, and k_1 is the detection efficiency for the $0^+ \rightarrow 2^+$ transition, respectively.

RUN		N_i(BG) counts/keV hr	Δ E keV	time hours	k_i %	Y_t counts	$T_{1/2}$ 10^{22}years	$0.53\ S_i(1/2)\sqrt{t}$ 10^{22}years
RUN 1	$0^+ \to 0^+$	1.8×10^{-3}	3.0	2115	100	3.8	2.0	1.8
	$0^+ \to 2^+$	7.6×10^{-4}	2.7	2115	34	1.7	1.2	1.1
RUN 2	$0^+ \to 0^+$	6.5×10^{-4}	3.0	1600	100	3.2	2.2	3.1
	$0^+ \to 2^+$	1.6×10^{-4}	2.5	1600	34	1.2	1.9	1.7
RUN 3	$0^+ \to 0^+$	6.2×10^{-4}	3.0	6977	100	4.5	6.9	6.4
	$0^+ \to 2^+$	2.7×10^{-4}	2.5	6977	34	2.5	4.2	3.6
RUN2 + RUN3	$0^+ \to 0^+$			8577		5.1	7.4	7.1
	$0^+ \to 2^+$			8577		2.3	5.6	4.0

Table 3-1

The halflife limits of ^{76}Ge $0\nu\beta\beta$ decays. N_i(BG) is the observed background rate, ΔE is the energy resolution, k_i is the detection efficiency for every transition, Y_t is possible hidden true counts in the continuum backgrounds. The halflives estimated from the sensitivities are also given in the table.

Author	Group	Year	Source	Resolution	m_ν and C.L.	References
Bergkvist	Stockholm	1972	^3H IN Al	50 eV	< 55 eV 90 %	Bergkvist72
Tretjakov etal	ITEP (Moscow)	1976	valin ($C_5H_{11}NO_2$)	45 eV	< 33 eV 90 %	Tretjakov76
Lubimov etal	ITEP (Moscow)	1980	valin ($C_5H_{11}NO_2$)	45 eV	$14 < m_\nu < 46$ eV 99 %	Lubimov80
Simpson	Guelph(Canada)	1981	^3H implant in Si	220 eV	< 60 eV 95 %	Simpson81
Boris etal	ITEP (Moscow)	1983	valin ($C_5H_{11}NO_2$)	20 eV	> 20 eV 95 %	Boris83

Table 4-1
The determination of electron anti-neutrino mass in tritium β-decay.

Group	Person	Method (Spectrometer and tritium souece)	Goal	References
Chalk River	Graham	Air-core $\pi\sqrt{2}$ spectrometer Multi-strip source	$m(\nu) \sim 20$ eV $\Delta E = 16 \sim 20$eV	Graham84
Stockholm	Bergkvist	Iron-yoked $\pi\sqrt{2}$ type< high luminosity Newly improved electromagnetic spectrometer		Bergkvist84
Livermore Rockfeller Fermi Laboratory	Fackler Mugge	Electrostatic spectrometer High activity flozen tritium molecule	$m(\nu) \sim 4$ eV $\Delta E \sim 2$ eV	Fackler84 Fackler85
Los Alamos Rockfeller Fermi Laboratory	Bowlesler Wilkinson Robertson	5-fold trochoid magnets, wire chamber Atomic beam tritium	$m(\nu) \sim 10$ eV	Bowles82 Bowles83 Robertson84
INS (Tokyo)	Ohshima et.al.	Iron free air-core $\pi\sqrt{2}$ spectrometer 2 molecular layer cooled at -100 ℃	$m(\nu) \sim 10$ eV $\Delta E \sim 9$ eV	Kawasaki85

Table 4-2
The plans for future tritium β-decay experiments.

Osaka Univ. Sea-level Laboratory

$E(\gamma_0)$ (MeV)	k_γ (%)	E_γ (MeV)	N_S(BG) (counts/keV·year)	N_A(BG)	N_C(BG)	ε_S(RI) ($\times 10^{-15}$)	ε_A(RI)	ε_C(RI)
1.0	9.5	2	4450	85	13	1.1	0.15	0.18
2.0	5.8	3	1450	13	3.5	1.3	0.12	0.18
3.0	4.4	4	830	5.8	0.66	1.5	0.12	0.11

Table 4-3(a) Sensitivities with the ELEGANTS for the detection of weak γ-ray(γ_0). Values in the table are at the sea-level laboratory of Osaka Univ.. k_γ is the peak efficiency of the ELEGANTS for γ_0, N_i(BG) is the observed background rate for mode i, respectively. The sensitivity ε_i(RI) gives roughly the lower limit on the activity in units of Curie for one year measurement. The suffices (S, A, C and G) stand for the modes of the measurement. S: singles, A: anticoincidence with all signals from the 4π γ-counter for the single γ_0 emitter, C: coincidence with a 550 keV γ_1 detected in one of the 4π-NaI segments for the γ_0 being accompanied by the γ_1, G: singles at Kamioka with nitrogen gas circulation.

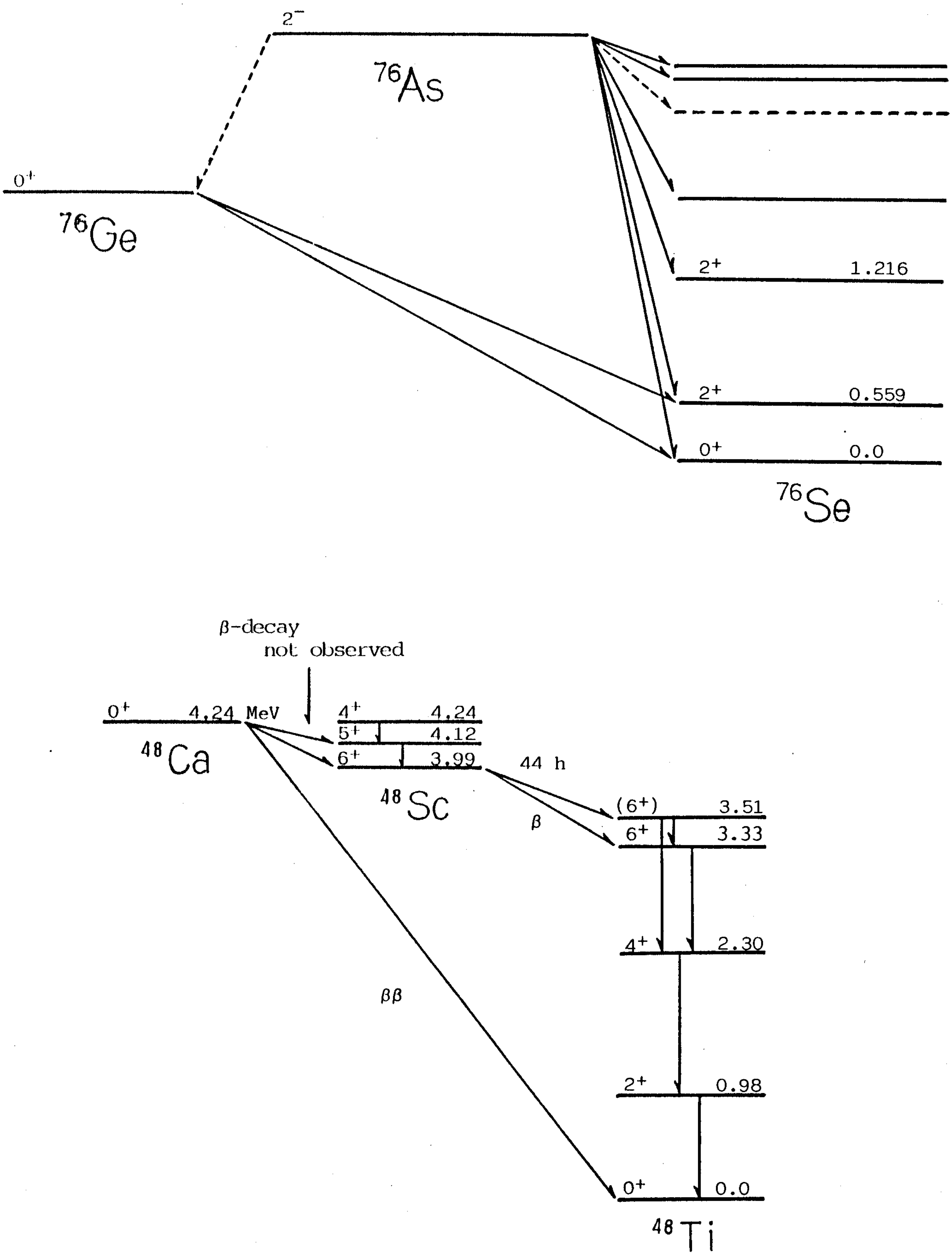
Kamioka Underground Laboratory

$E(\gamma_0)$ (MeV)	k_γ (%)	E_γ (MeV)	$N_G(BG)$ (counts/keV·year)	$N_A(BG)$	$N_C(BG)$	$\varepsilon_G(RI)$ ($\times10^{-15}$)	$\varepsilon_A(RI)$	$\varepsilon_C(RI)$
1.0	9.5	2	440	57	12	0.35	0.13	0.17
2.0	5.8	3	36	5.3	2.5	0.15	0.08	0.15
3.0	4.4	4	1.9	1.3	0.04	0.07	0.06	0.03

Table 4-3(b) Sensitivities with the ELEGANTS for the detection of weak γ-ray(γ_0). Values in the table are at the Kamioka underground laboratory. (See captions of Table 4-3(a))

Chain	Source	E_γ (keV)	k_γ (%)	b_G (%)	N_G(BG) (counts/year)	ε_G(NRI) ($\times 10^{-15}$)
^{238}U	^{214}Bi	609	13.5	42.6	23800	2.3
		1120	8.8	13.9	6300	5.6
		1764	6.3	14.6	7000	7.8
^{232}Th	^{208}Tl	583	13.9	85.8	4560	0.44
		860	10.6	12.0	650	1.7
		2614	4.8	99.8	3950	1.1
^{40}K	^{40}K	1461	7.3	10.7	34800	20

Table 4-4 Sensitivities of the ELEGANTS for the detection of natural radioactivities. Here quotes the values at the Kamioka underground laboratory. k_γ is the peak efficiency of the ELEGANTS for the γ-ray, b_G is the branching ratio of the emission for the decay, respectively. (See caption of Table 4-3)



2⁻
76As
0⁺
76Ge
2⁺ 1.216
2⁺ 0.559
0⁺ 0.0
76Se
β-decay
not observed
0⁺ 4.24 MeV
48Ca
4⁺ 4.24
5⁺ 4.12
6⁺ 3.99
48Sc
44 h
β
ββ
(6⁺) 3.51
6⁺ 3.33
4⁺ 2.30
2⁺ 0.98
0⁺ 0.0
48Ti

Fig. 1-1

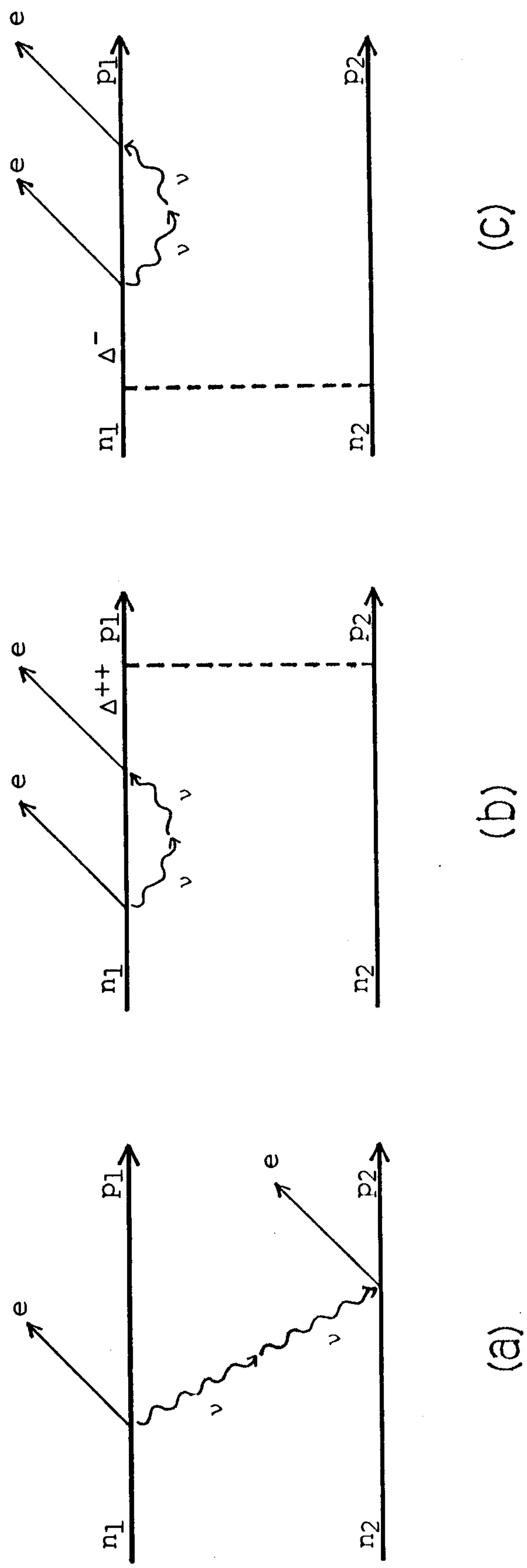


Fig. 1-2

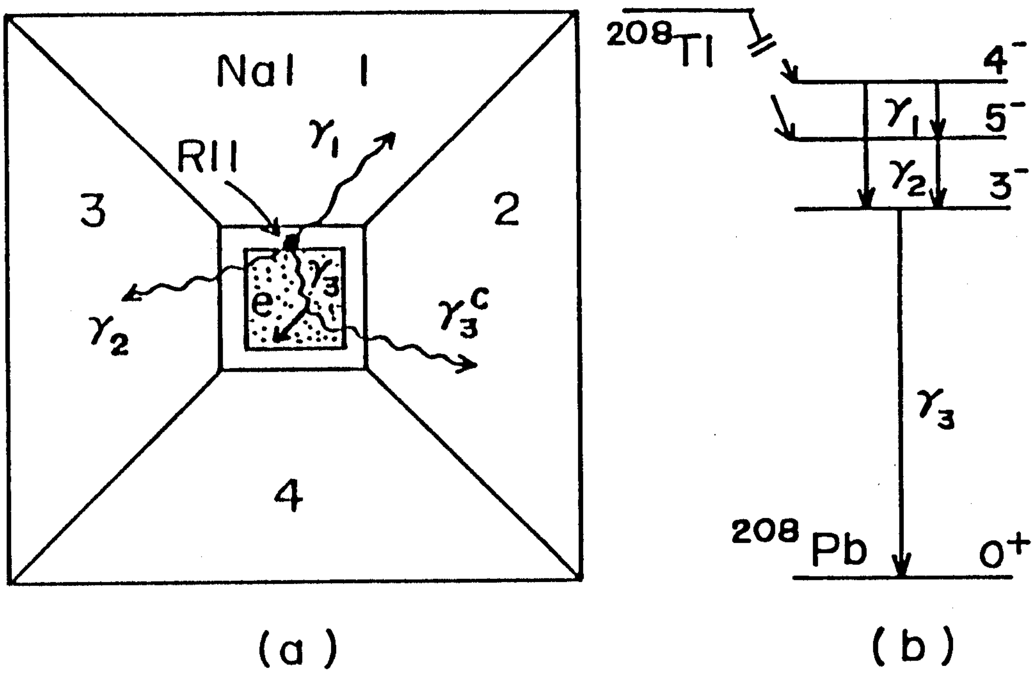


Fig. 2 - 1

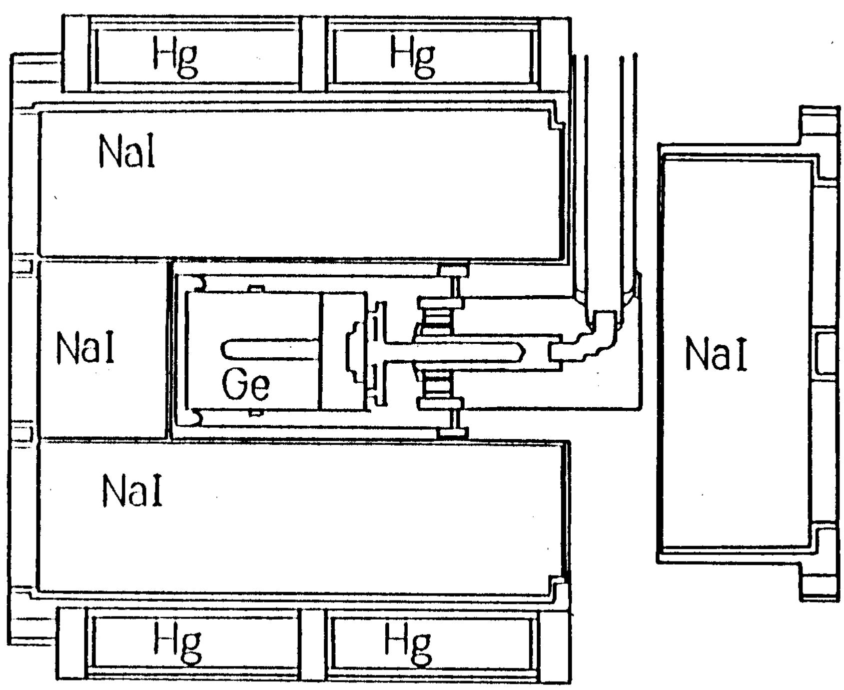


Fig. 2 - 2 (a)

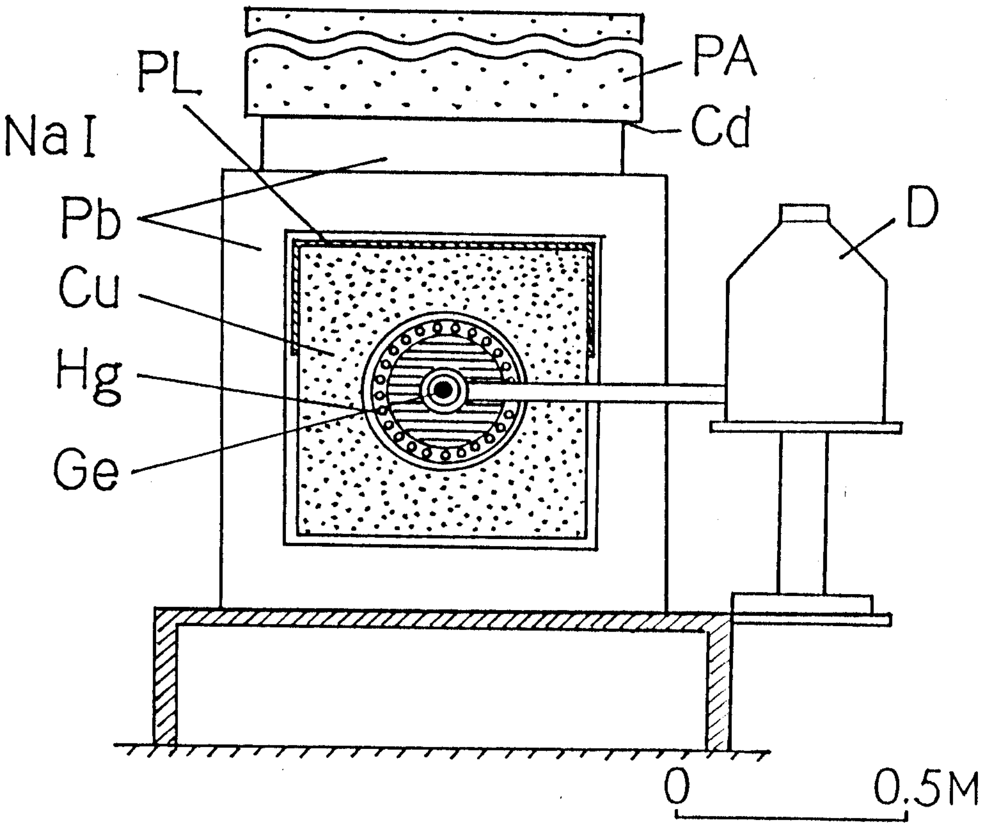


Fig. 2-2 (b)

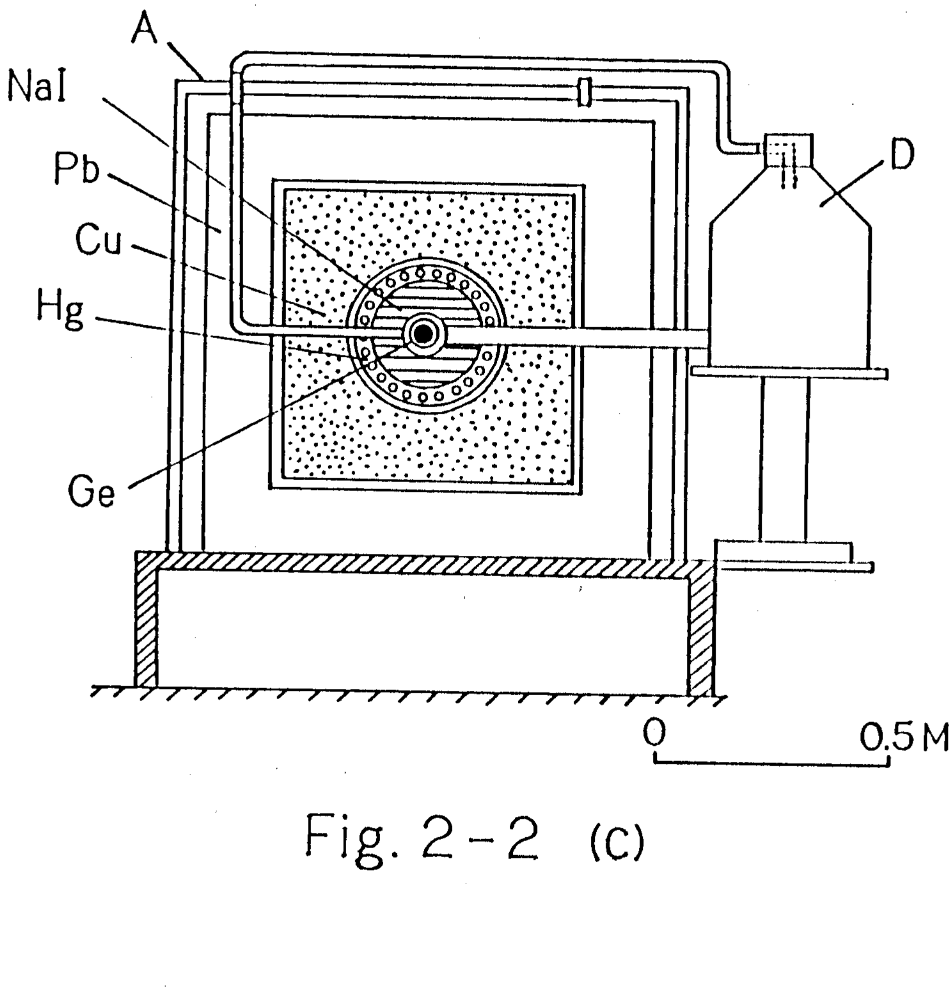


Fig. 2-2 (c)

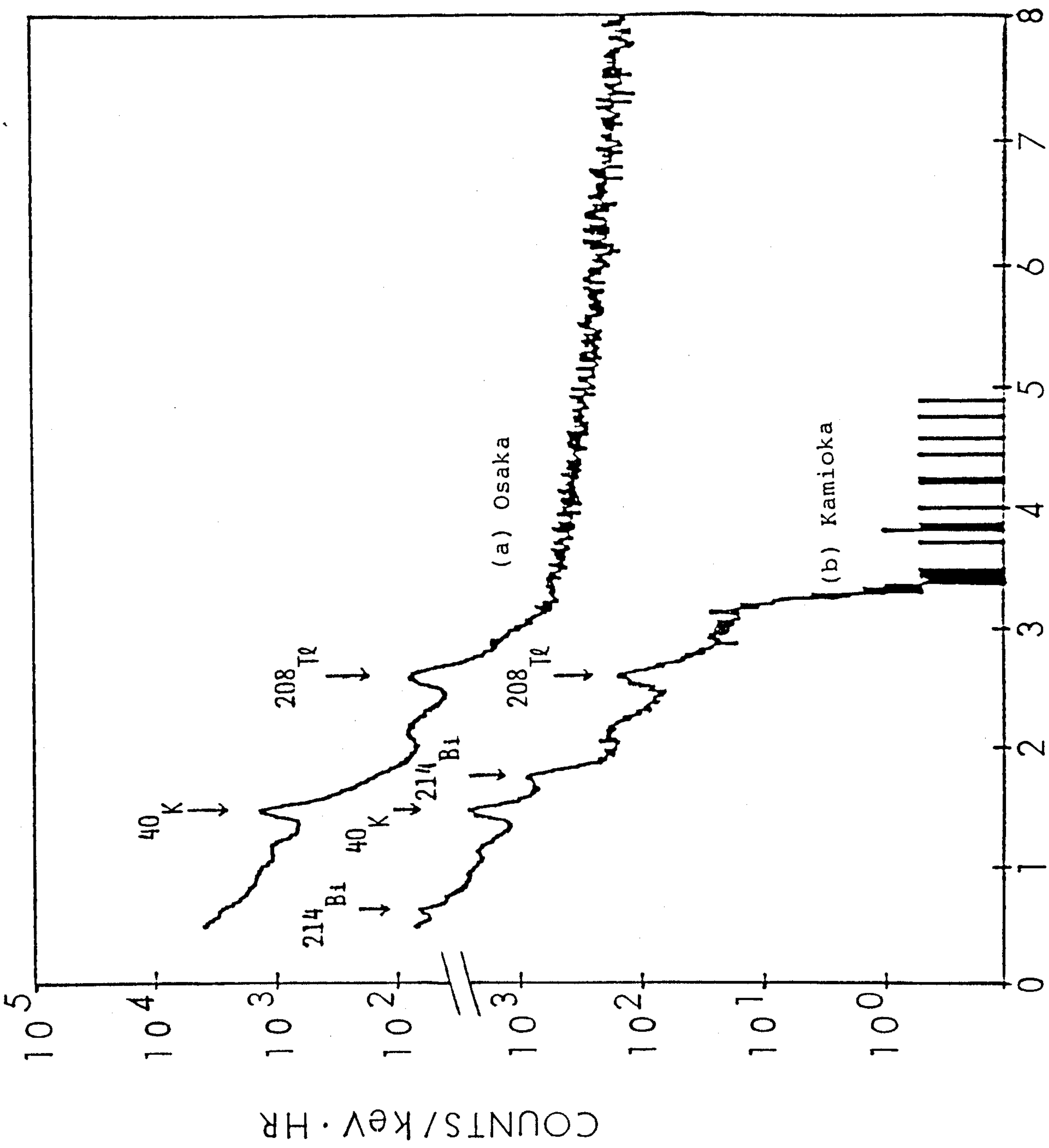
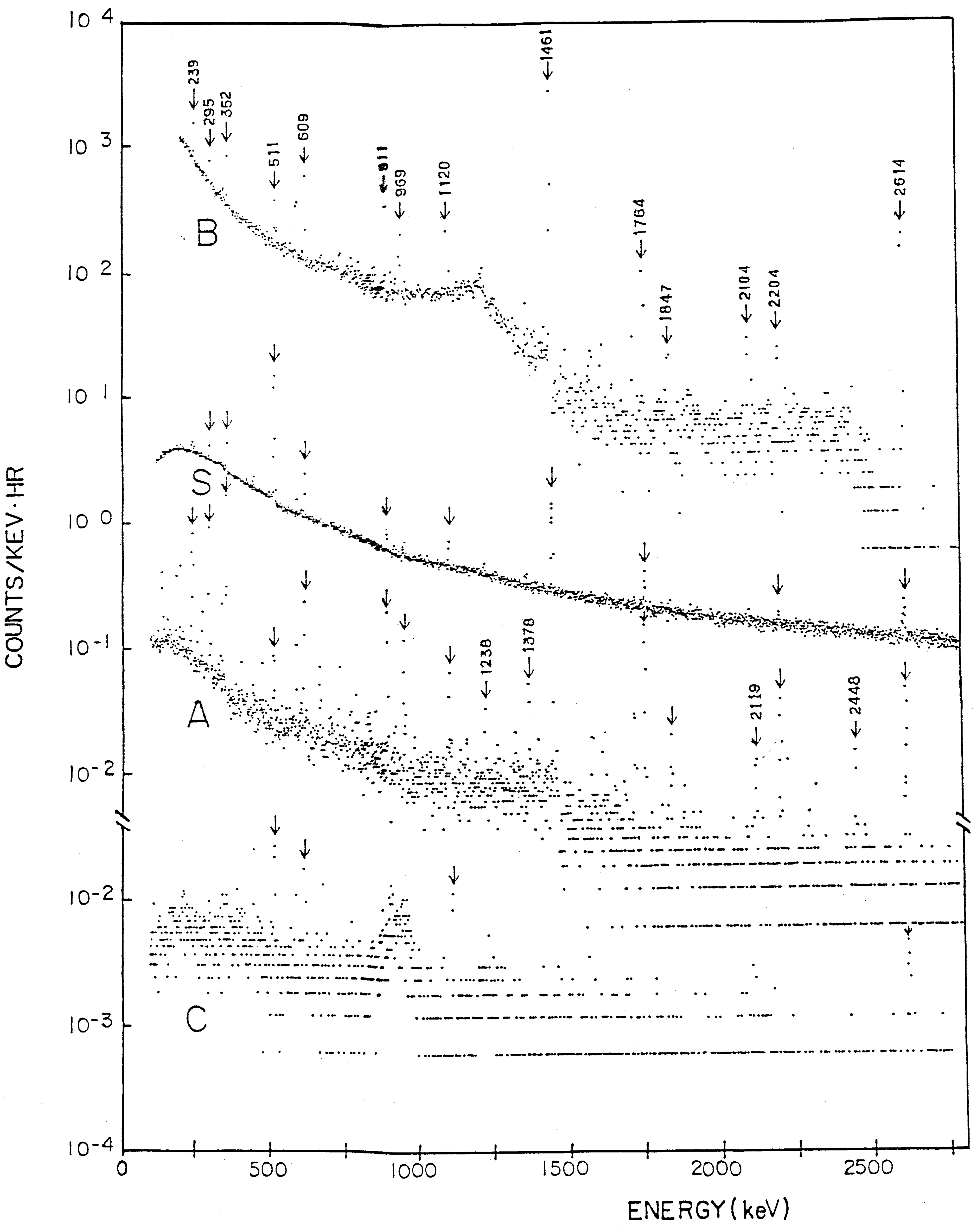


Fig. 2-3



COUNTS/KEV·HR
ENERGY(keV)
B
S
A
C
239
295
352
511
609
911
969
1120
1461
1764
1847
2104
2204
2614
1238
1378
2119
2448

Fig. 2-4 (a)

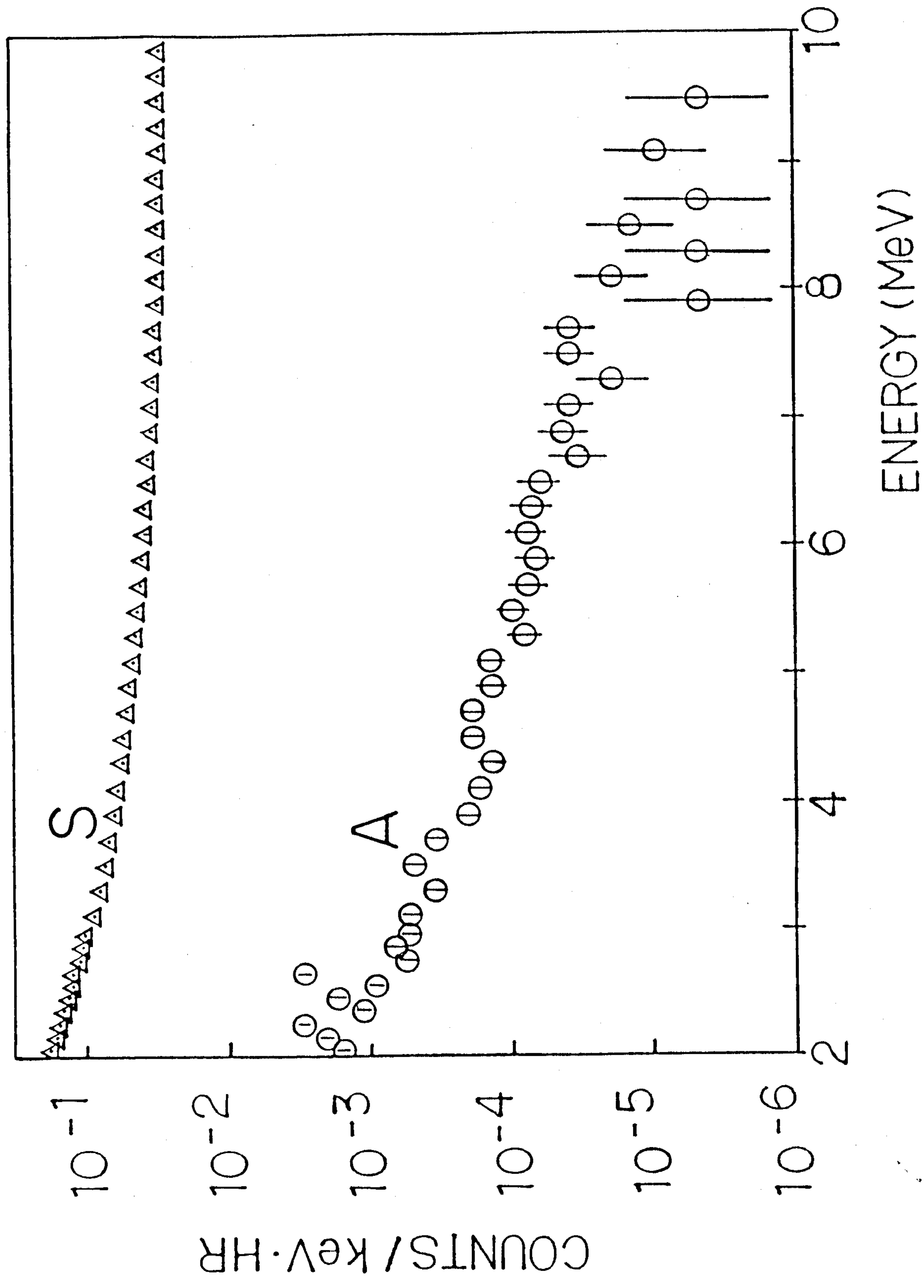
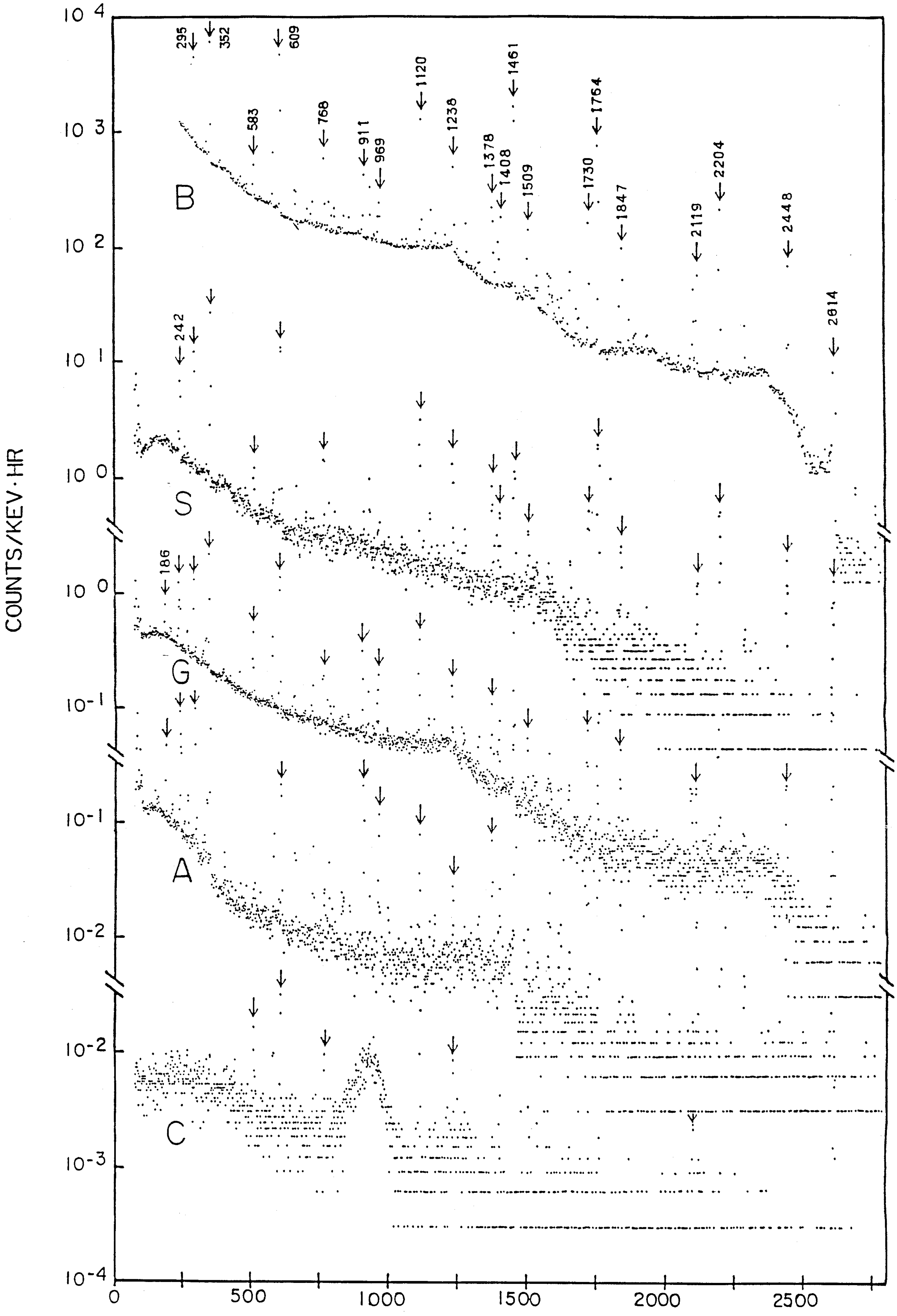


Fig.2-4 (b)



COUNTS/KEV·HR
ENERGY(keV)
B
S
G
A
C
295
352
609
583
768
911
969
1120
1238
1378
1408
1461
1509
1730
1764
1847
2119
2204
2448
2614
242
186

Fig. 2-5 (a)

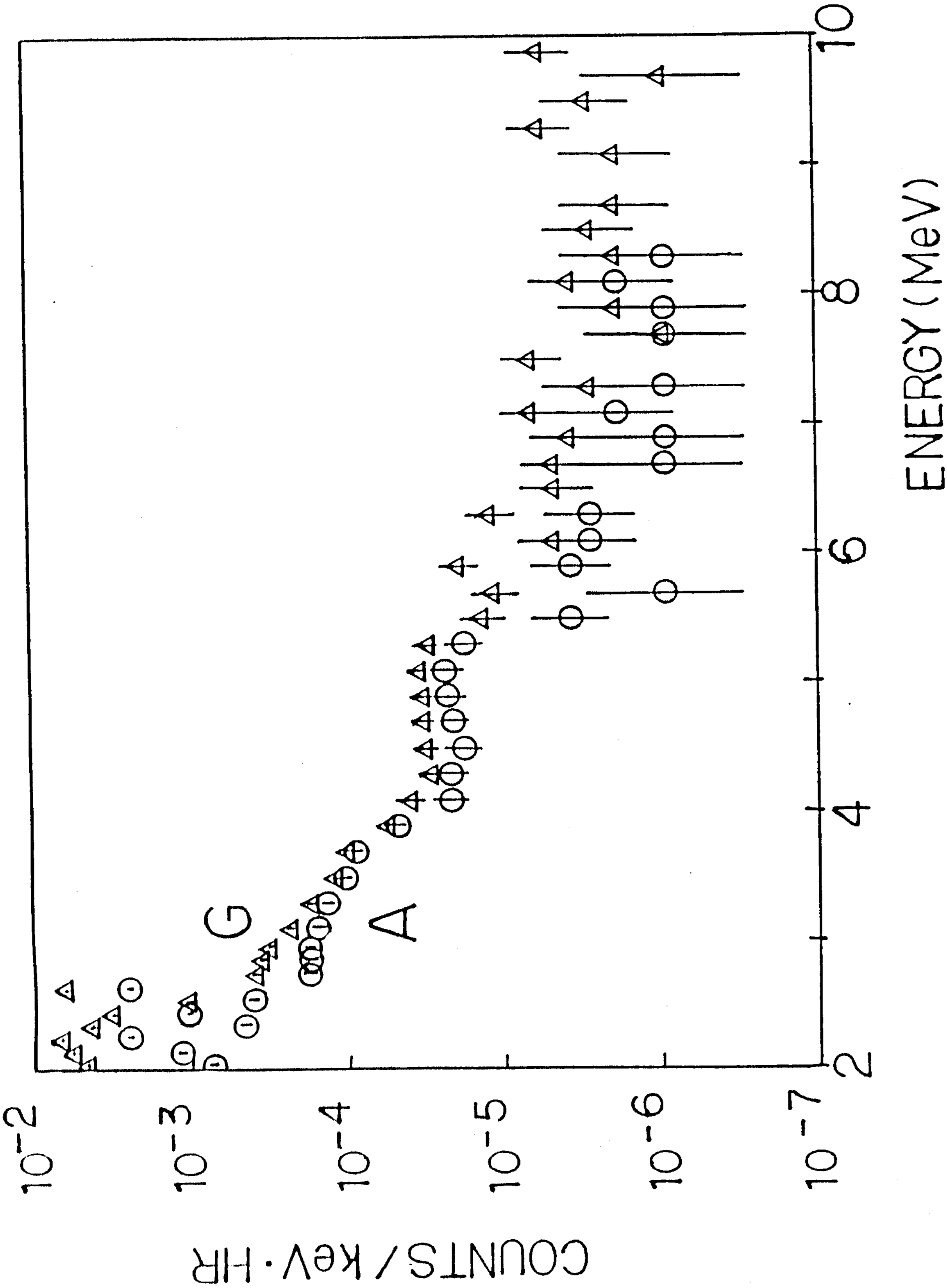
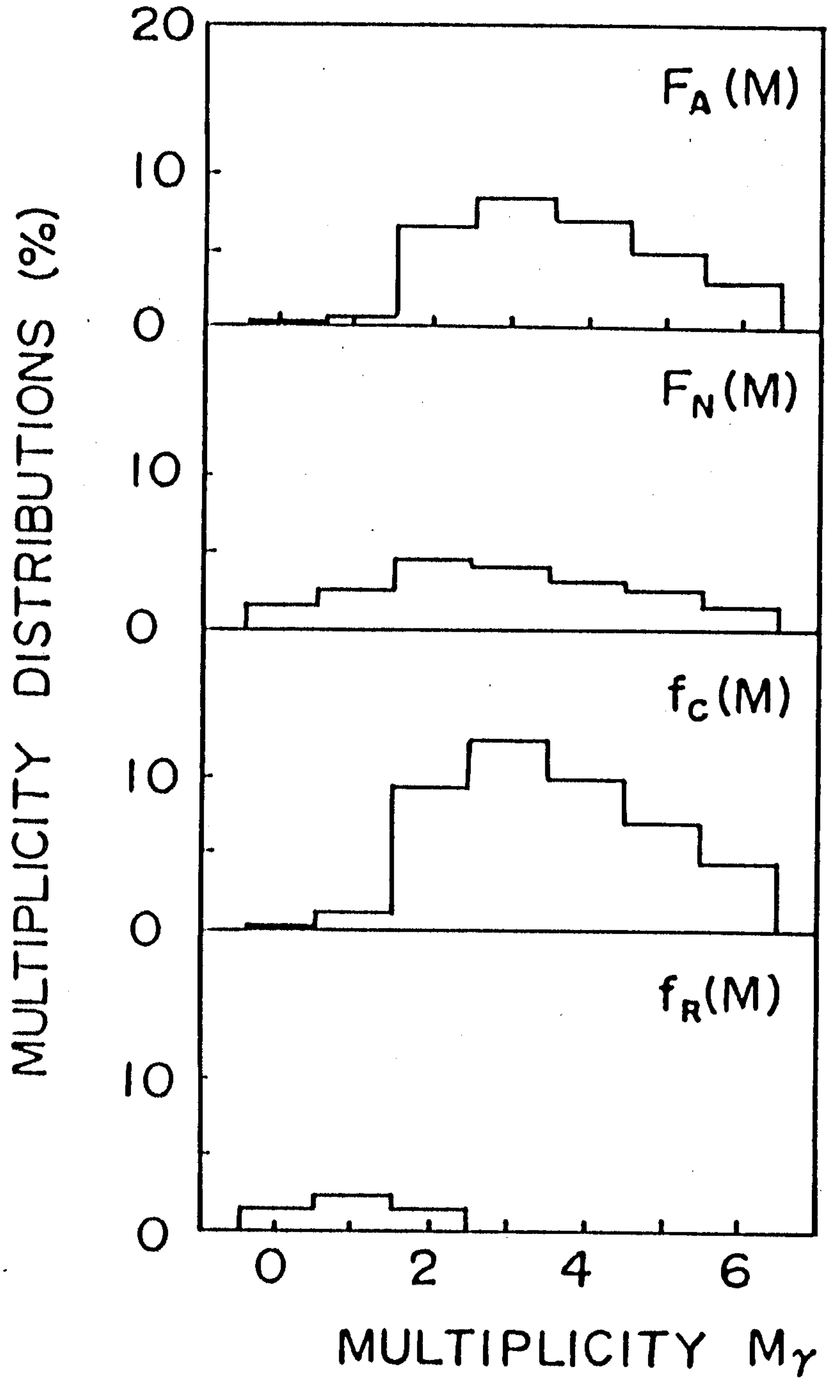


Fig. 2-5 (b)



20
10
0
$F_A(M)$
$F_N(M)$
$f_C(M)$
$f_R(M)$
MULTIPLICITY DISTRIBUTIONS (%)
0
2
4
6
MULTIPLICITY M_γ

Fig.2-6

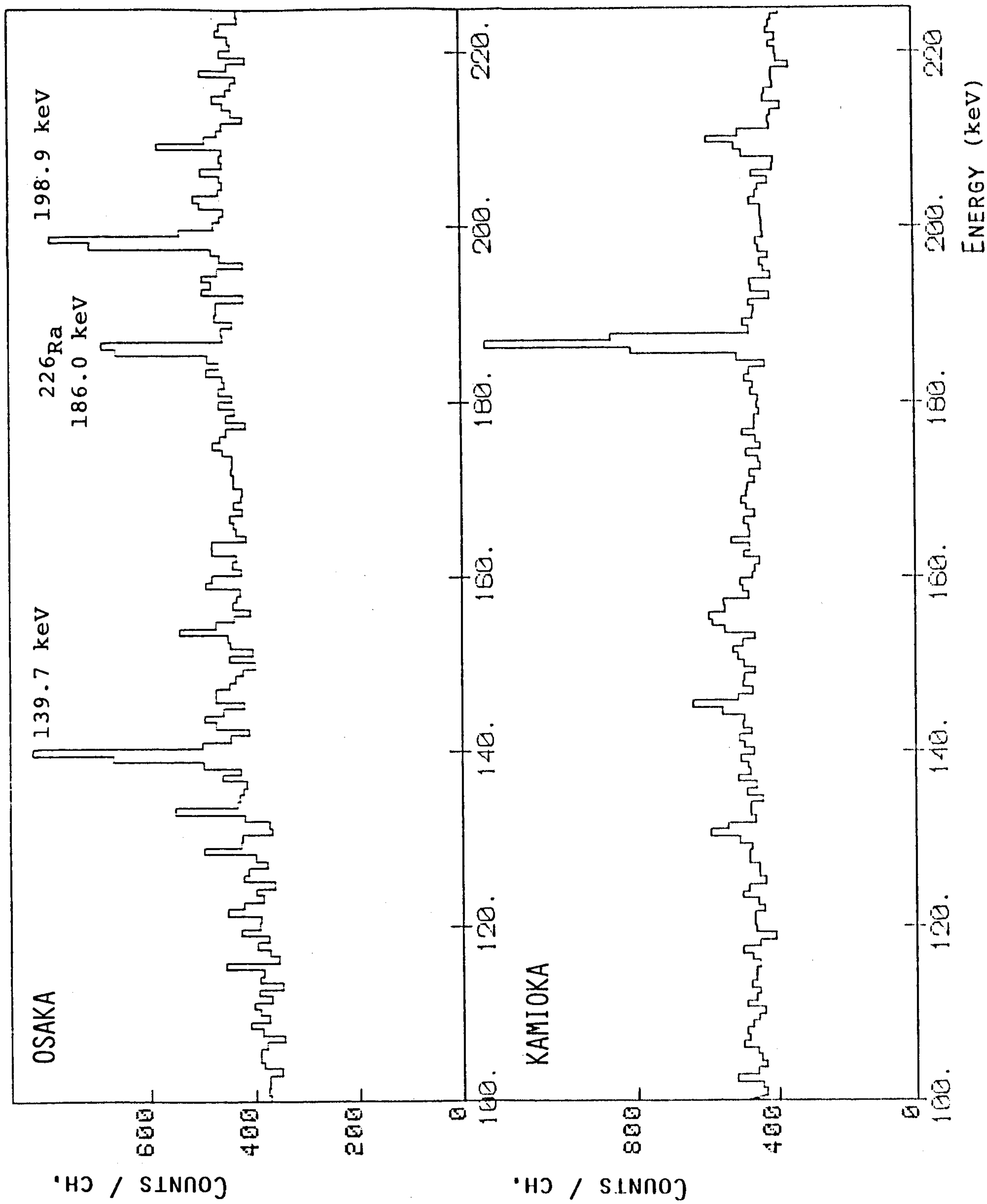

OSAKA
KAMIOKA
139.7 keV
226Ra
186.0 keV
198.9 keV
COUNTS / CH.
ENERGY (keV)

Fig. 2-7

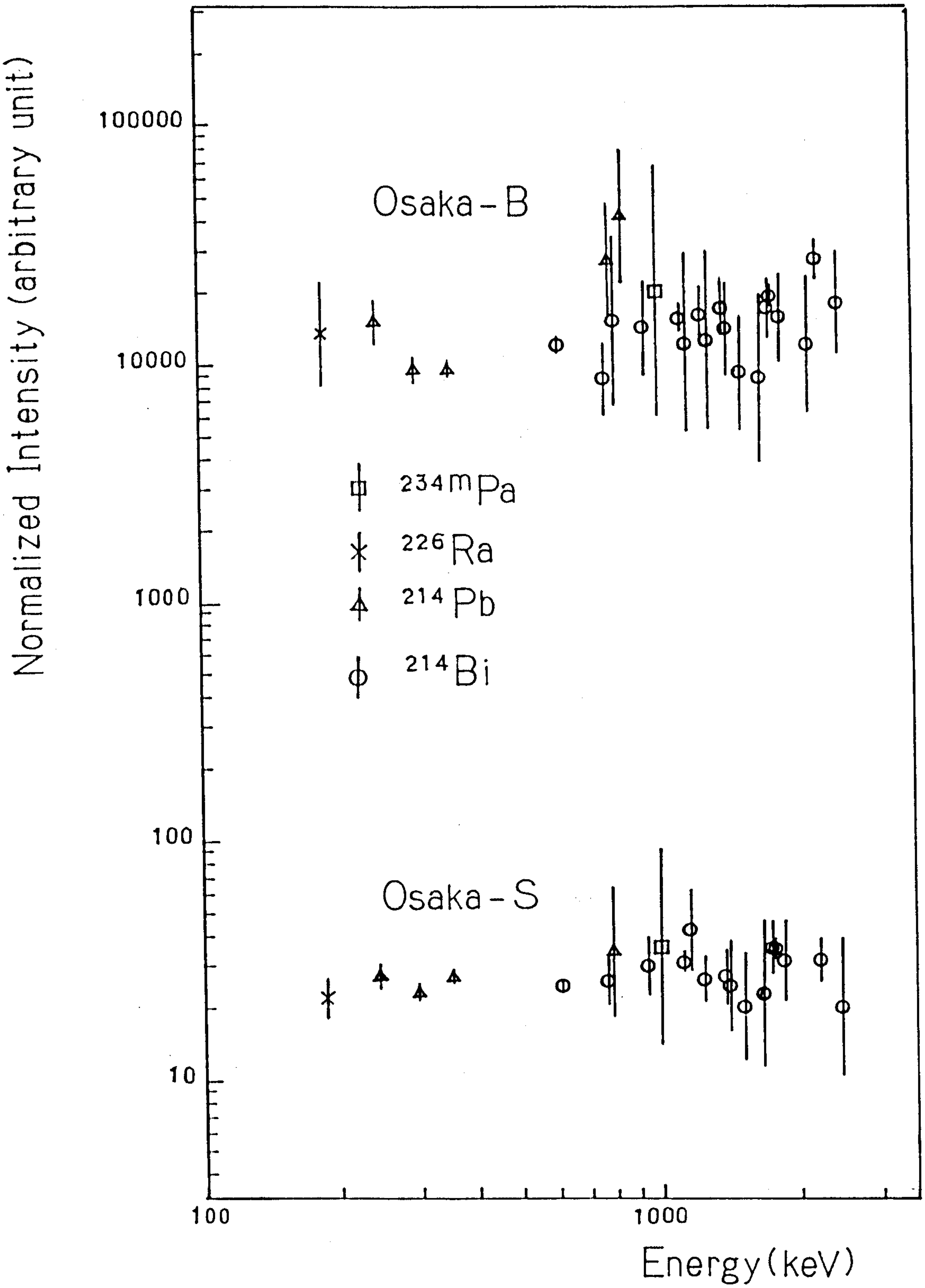
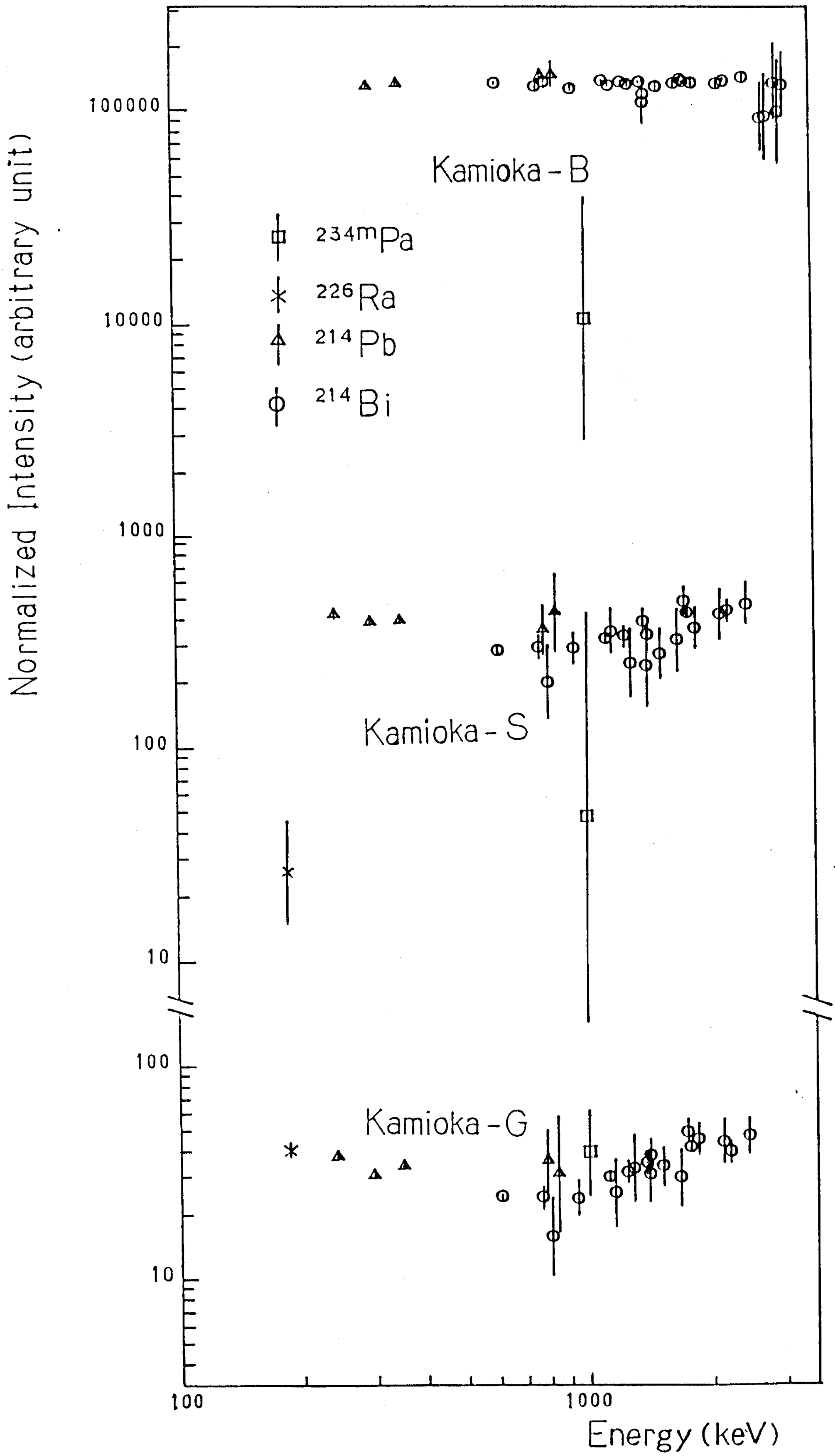

Normalized Intensity (arbitrary unit)
100000
10000
1000
100
10
Osaka-B
Osaka-S
234mPa
226Ra
214Pb
214Bi
100
1000
Energy(keV)

Fig. 2-8 (a)



Normalized Intensity (arbitrary unit)
100000
10000
1000
100
10
100
10
Kamioka - B
234mPa
226Ra
214Pb
214Bi
Kamioka - S
Kamioka - G
100
1000
Energy (keV)

Fig. 2-8 (b)

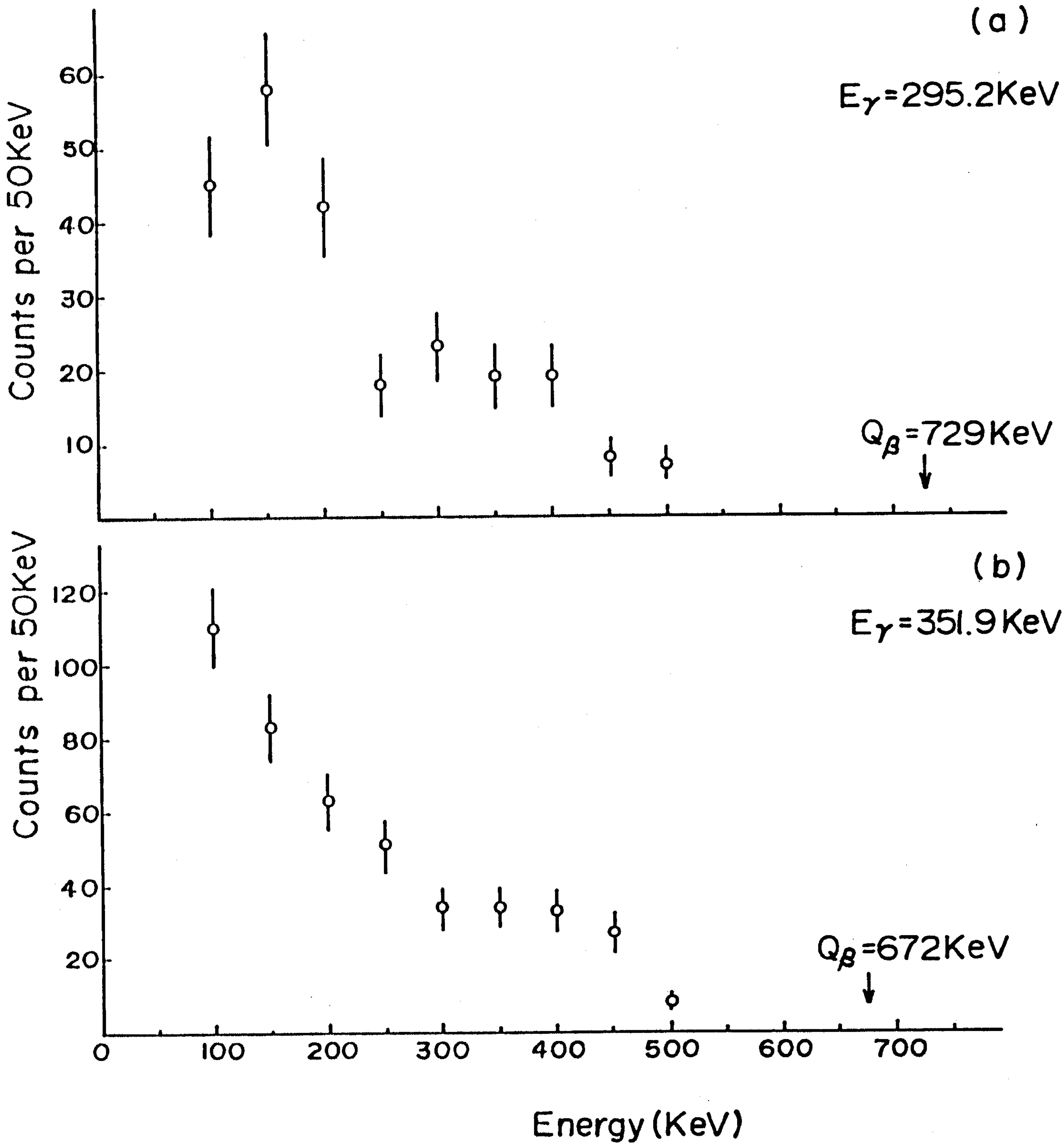

(a)
Eγ=295.2KeV
Qβ=729KeV
Counts per 50KeV
60
50
40
30
20
10
(b)
Eγ=351.9KeV
Qβ=672KeV
Counts per 50KeV
120
100
80
60
40
20
0
100
200
300
400
500
600
700
Energy (KeV)

Fig. 2-9

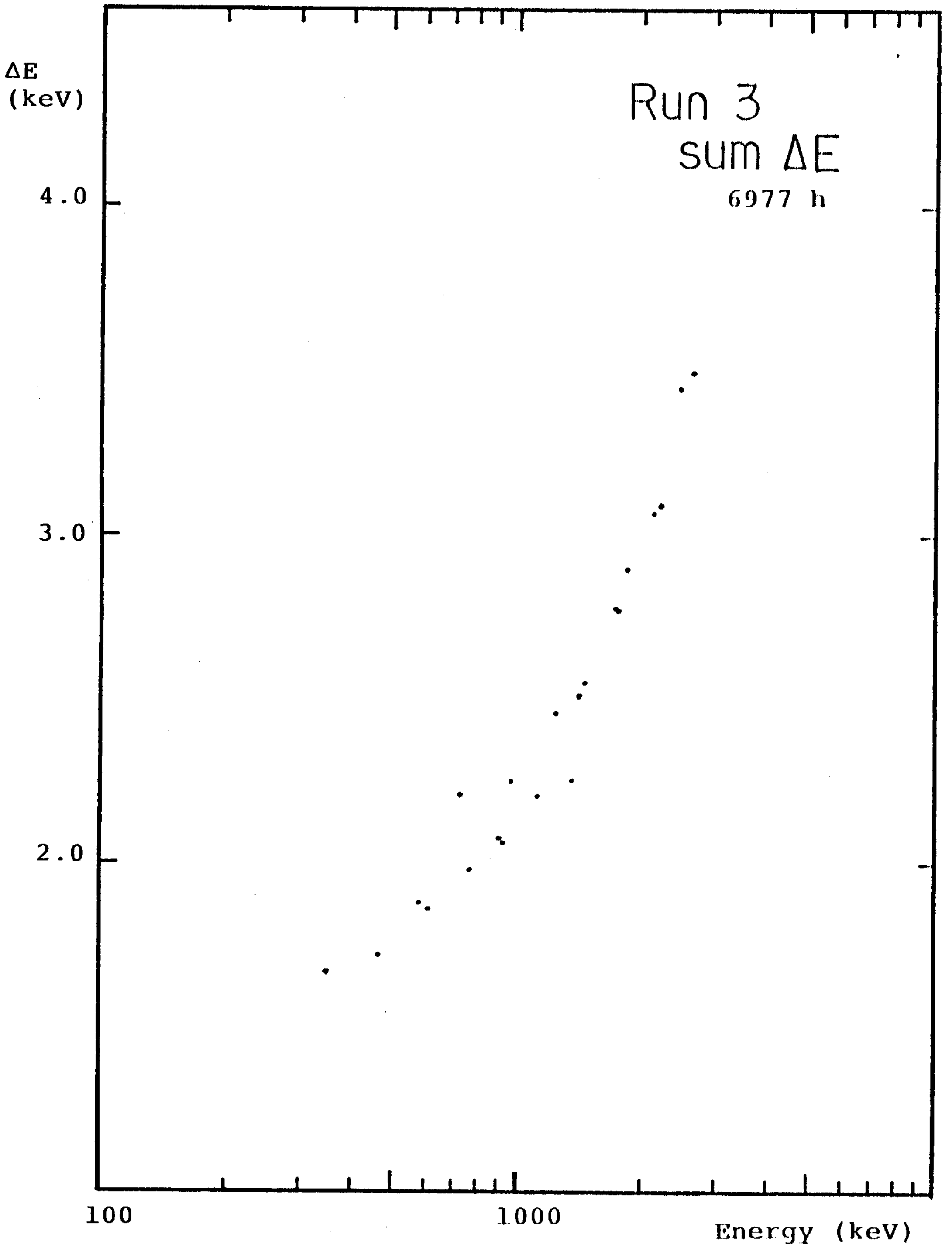


Fig. 3-1

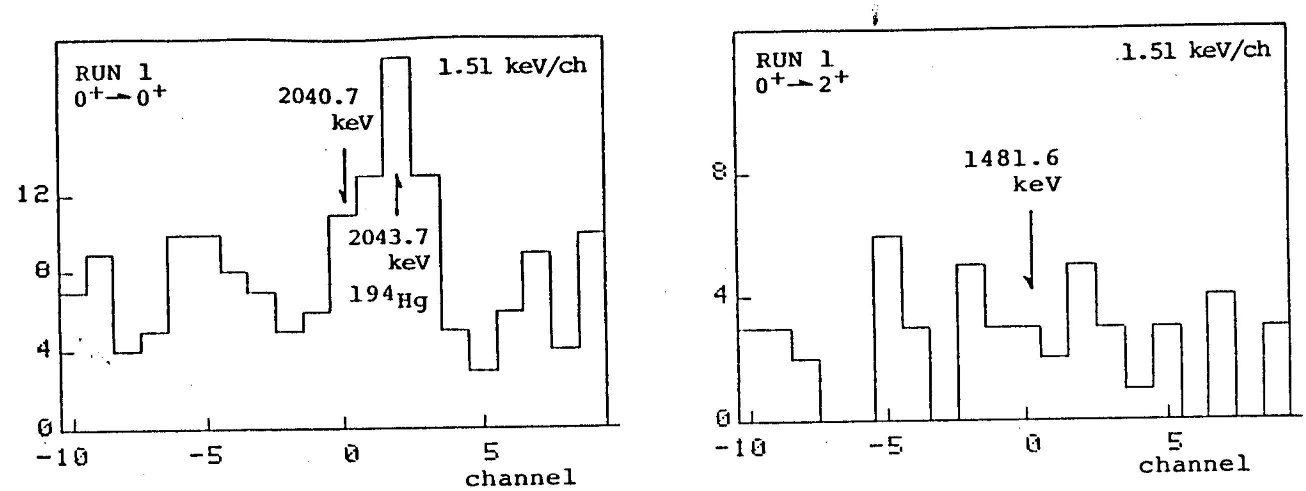


Fig.3-2 (a)

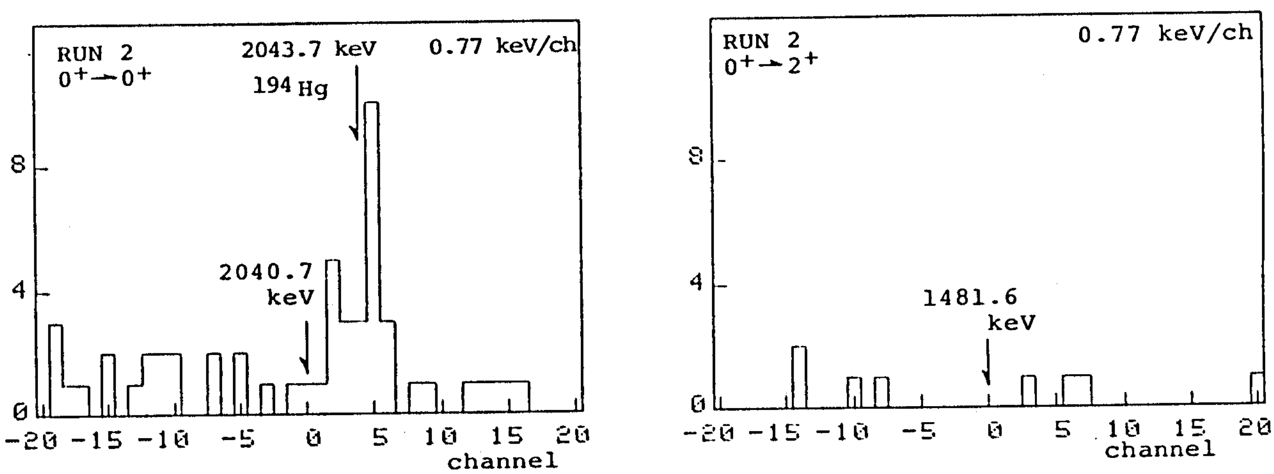


Fig.3-2 (b)

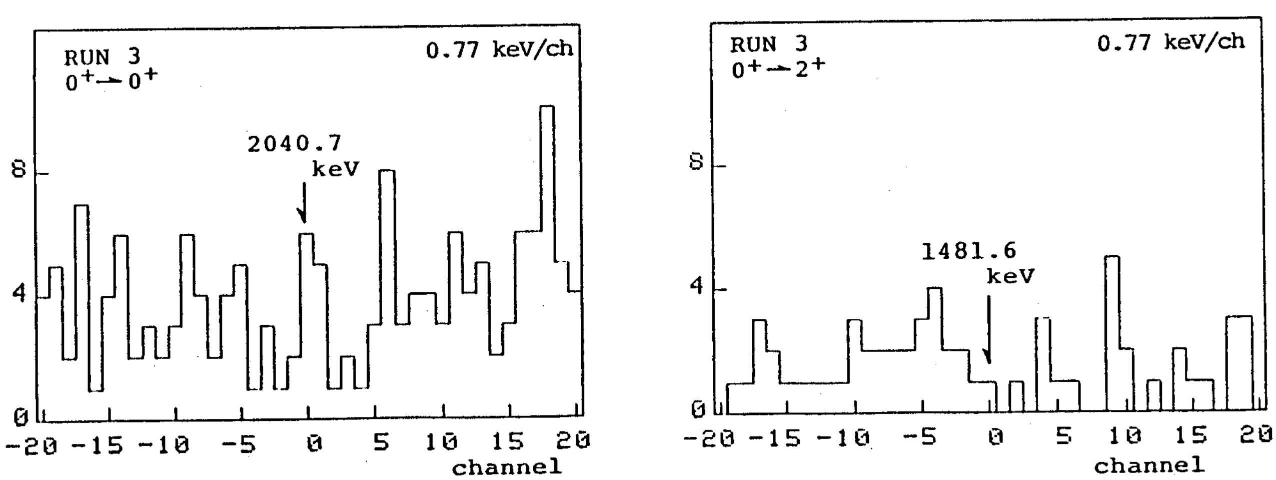


Fig.3-2 (c)

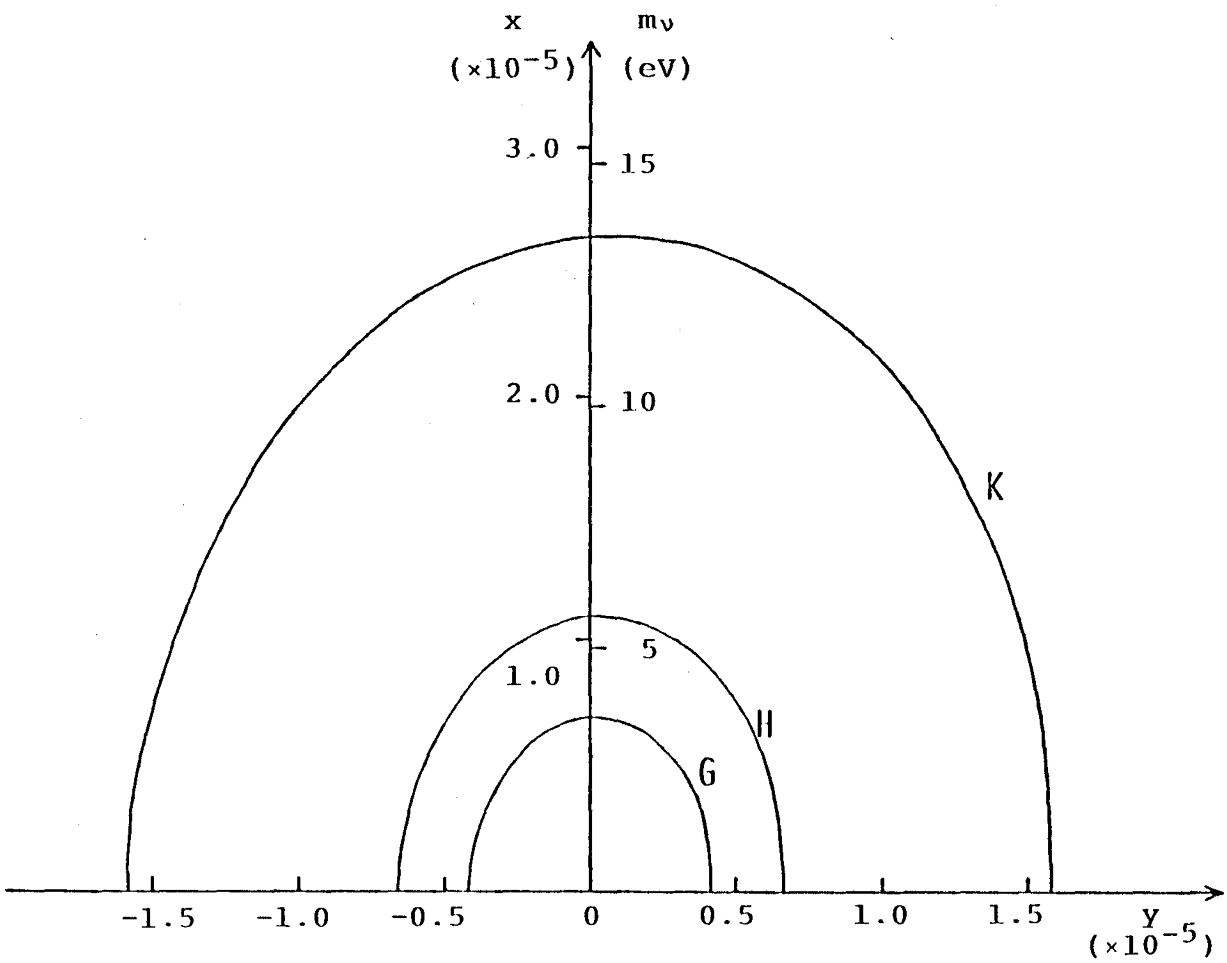


Fig. 3-3

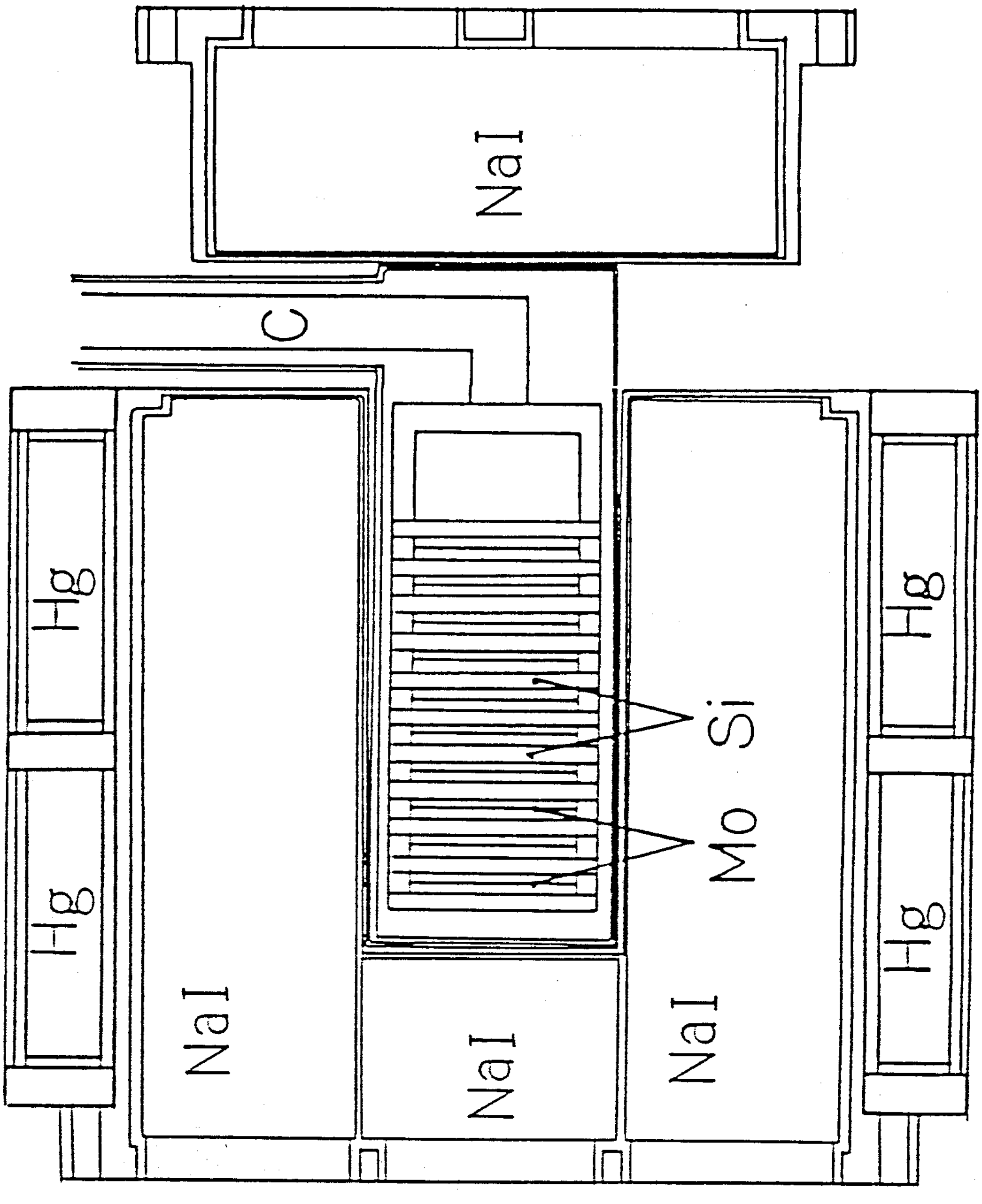


Fig. 4-1