Construction of a Thin Lens Type Beta-Ray Spectrometer

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A thin lens type beta-ray spectrometer was designed and constructed. Two-fold designs were made, in which the focal length of the magnetic lens is 15cm and 30cm respectively. The parameters and the properties of this spectrometer are given.

I. INTRODUCTION

In our laboratory, a beta-ray spectrometer was indispensable to the research of the β- and γ-rays emitted from radioisotopes made by the Kyoto University Cyclotron, when the construction of this cyclotron was going on. After the inquiry of many types of spectrometers, it was decided to construct a thin lens type spectrometer for its feasibility.

Leading principles of our design were as follows: (1) to get the maximum transmission with a reasonable resolution, (2) to be suitable to analyze reaction γ-rays, and (3) to be able to study β-γ coincidences and β-γ angular correlations. The maximum γ-ray energy to be measured was decided to be in the range from 4 MeV to 6 MeV, because the γ-rays emitted by radioisotopes with relevant life times have energies below this range.

In the following sections, the outline of the spectrometer in our laboratory is described, and some properties obtained in its operation are given.

II. DESIGN OF THE BETA-RAY SPECTROMETER

II. 1. The Magnetic Lens

There are three types of the coil cross section: (1) the approximately square one which was used by Deutsch *et al.*[1] and by Siegbahn[2)3)], (2) the rectangular one which is long in radial direction like the Iowa State College spectrometer[4)5)], and (3) the rectangular one which is long in axial direction like the one designed by Hornyak[6)].

Although there are no clear reasons to decide which is the best, it may be true that the type (1) has larger spherical aberration than the type (2) and that the ring focusing position of the type (1) is not so close to the axis as the type (2). The type (1) seems to be more convenient than the type (2) to adjust the ring baffles. In addition, the amount of the copper wire giving the same focal length is less in the type (1) than in the type (2). Few examples of the

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type (3) were constructed and its properties were not especially good. From these reasons the type (1) was adopted.

As mentioned above, this type has rather large spherical aberration. A method was proposed by Quade and Halliday[7] to reduce the aberration in which the coil was divided into two or four pieces and rearranged coaxially. Dividing the coil, however, results in difficulty to coincide the coil axes with one another. It seemed to be preferable to improve the resolution rather by careful use of ring focusing than by reduction of spherical aberration with the separated coils.

The cylinder of the spectrometer was made of high quality aluminium. Its inner and outer diameters are 20.0cm and 21.4cm respectively. There are two cylinders: one is 100cm long and is used in the case of 15cm focal length, the other 120cm long and used in the case of 30cm focal length. Coil design parameters are given in Table 1.

Table 1. Specifications of the coil.

Dimensions of the coil		
	inner radius	12.4 cm
	outer radius	30.2 cm
	axial thickness	17.5 cm
Ampere-turns		56,000
Total turns		1,120
Total resistance		1.769 Ω (75°C)
Cross section of the copper wire		2.2×8.0 mm^2
Weight of the copper wire		232.0 kg
Maximum current density		2.86 amp/mm^2
Total weight of the coil		450.0 kg
Maximum β-ray energy		6.0 MeV (focal length 30 cm)
		4.0 MeV (focal length 15 cm)
Motor generator		5.0 KW (100V-50amp maximum)

The coil was cooled by water flowing through cooling pipes attached to the copper plates (3.2 mm in thickness) inserted into every two coil pan-cake layers.

II. 2. Calculation of Electron Trajectories

When electrons are detected by a spectrometer with focal length of 30 cm and with a cylinder of 20 cm in inner diameter, it seems to be difficult to get higher transmission than about 0.7%. To increase the transmission, it is necessary to reduce the distance between the source and the detector, namely to shorten the focal length. In this case, two disadvantages occur: (1) the maximum energy of β-rays to be measured becomes smaller when the same coil is employed, (2) the emission angle becomes larger and the spherical aberration becomes more conspicuous. The dispersion of the β-rays at the position of the detector becomes large and a detector with a wide aperture must be used. Transmission as high as possible, however, is often desired. It was intended to investigate the relation between resolution and transmission for an unusually short focal length. The design study of the spectrometer with the focal length of 15 cm was made together with that of 30 cm.

The method of calculation was based essentially on the formulation given by Deutsch *et al.*[1] and Keller *et al*[4]. From the equations of motion for an electron in a cylindrically symmetric magnetic field, a single equation for an electron trajectory can be obtained. The magnetic field is described by a vector potential which is always in an azimuthal direction. Energy and angular momentum about the axis of symmetry become constants of motion, and the time and the azimuthal variable can be eliminated. For any particle that starts at the axis, the angular momentum is zero, and the resulting equation for the trajectory (radial displacement r as a function of axial displacement z) is

$$r''(k^2-A^2)/(1+r'^2)-r'A(\partial A/\partial z)+A(\partial A/\partial r)=0$$

where A is the vector potential per unit magnetizing current, and k is the electron mementum in $H\rho$ units also divided by the magnetizing current. Primes indicate differentiation with respect to z. The vector potential A (r, z) was calculated from the field H_0 on the axis by the well-known expansion.

The actual computations involved in the numerical integration of this equation of motion were carried out by an electronic computer. The calculation

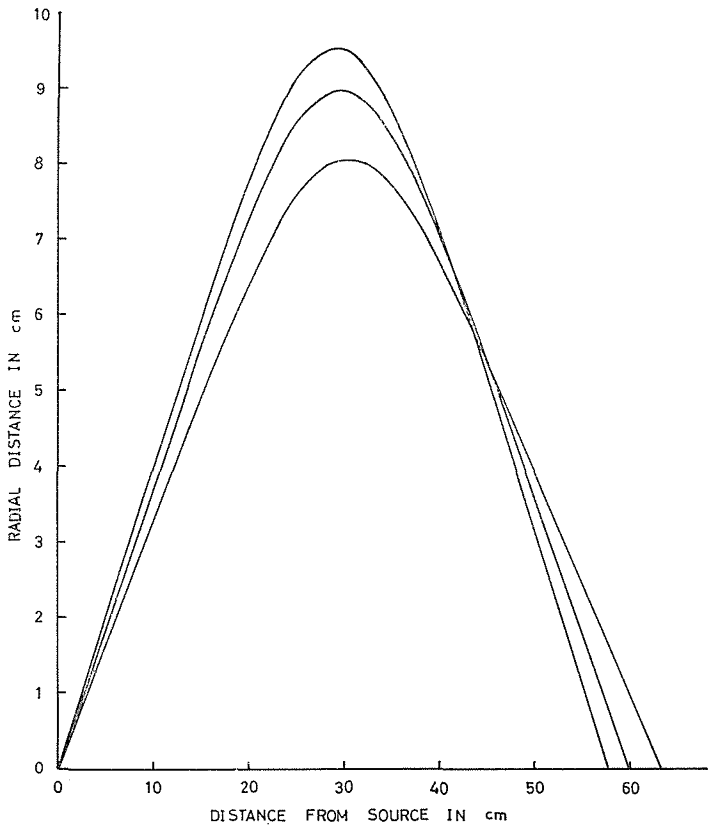

Fig. 1. Trajectories of electrons for a given momentum.

was made at 2 cm intervals in z. Twenty-four electron trajectories were calculated for a point source on the axis, using some values of momentum per unit magnetizing current and initial emission angle. For example, the set of trajectories for $k=294.54$ gauss cm/amp and the focal length of 15 cm is shown in Fig. 1.

As was expected, the position of the ring focus is considerably remote from the detector and the radius of the focusing ring is larger than one half of the cylinder radius.

From these trajectories of electrons, we determined the transmission curves by Perkins *et al.*'s graphical method[8] and examined optimum conditions, changing the location, radius and width of the ring slit, the counter aperture and the emission angle of electrons. These results are shown in Table 2.

Table 2. Calculated values of resolution and transmission.

	(A)	(B)	(C)	(D)
Distance between source and detector (cm)	60.0	60.0	120.0	120.0
Focal length (cm)	15.0	15.0	30.0	30.0
Magnification	1	1	1	1
Location of ring baffle from source (cm)	44.0	44.0	96.0	96.0
Inner radius of ring baffle (cm)	5.71	5.71	4.0	4.063
Outer radius of ring baffle (cm)	5.81	5.91	4.1	4.1
Width of ring slit (mm)	1.0	2.0	1.0	0.37
Detector aperture (cmϕ)	2.0	3.0	1.36	1.0
Emission angle, maximum	21°34′	22°20′	10°28′	10°12′
minimum	18°15′	17°27′	8°30′	8°54′
Transmission (%)	0.96	1.45	0.28	0.19
Resolution (%)	0.55	1.14	0.48	0.18

The values listed in the table were obtained by assuming a point source on the axis of the spectrometer. Therefore, if there is finite extension of the source, it may be expected for the transmission versus resolution character to become worse by a factor of two or three. In spite of these circumstances, it seems that the spectrometer with 15 cm focal length has a fairly good characteristics in comparison with those of the conventional type of 30 cm focal length.

III. CONSTRUCTION OF THE EQUIPMENTS

III. 1. Baffle System

In this report, only the case of 15 cm focal length is described. The dimensions of the spectrometer under consideration are shown in Fig. 2. The baffle system corresponds to the case of Table 2 (A). The distance between the source and the detector is 60 cm.

The entrance baffle limited the maximum emission angle to 21°34′, and its edge was tapered along the electron path with $k_0=294.54$ gauss cm/amp and the emission angle 21°34′, where k_0 is the electron momentum divided by the focus-

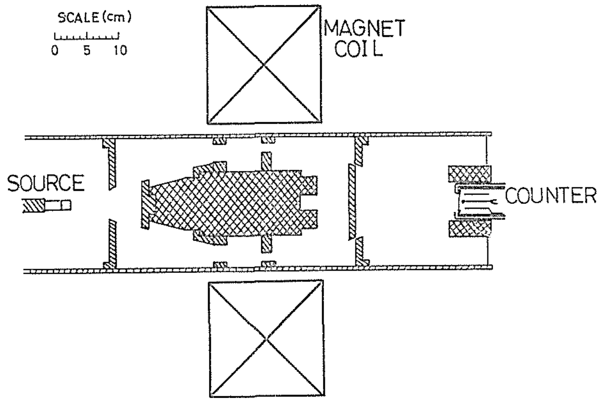

Fig. 2. Schematic diagram of the spectrometer.

ing current at the maximum transmission[8]. The center baffle was made of lead and served for shielding the detector from direct γ irradiation by the source. The ring baffles were located at the distance of 44 cm from the source. The radius of the inner baffle was 5.7 cm and the gap was 1 mm (see Fig. 2). The positions of the baffles were decided from the electron trajectories. The edge of the inner baffle was tapered along the trajectory of the minimum emission angle and the edge of the outer baffle was tapered properly to transmit all electrons of the chosen family.

An end window type G-M counter was used as a detector. Its window is 23 cm in diameter and is made of mica of 2.73 mg/cm^2 in thickness. The diameter of the cylindrical electrode is 20 mm. The lower limit of emission angle of electorons was confined to 18°15′ by the detector aperture.

III. 2. Vacuum System

A Kinney type rotary pump and a 6 inches oil diffusion pump system maintained a vacuum lower than 1.5×10^{-5} mmHg in the cylinder. Changing the source or the detector can be done without breaking the vacuum. The spectrometer cylinder and the evacuating pump system were connected with a brass

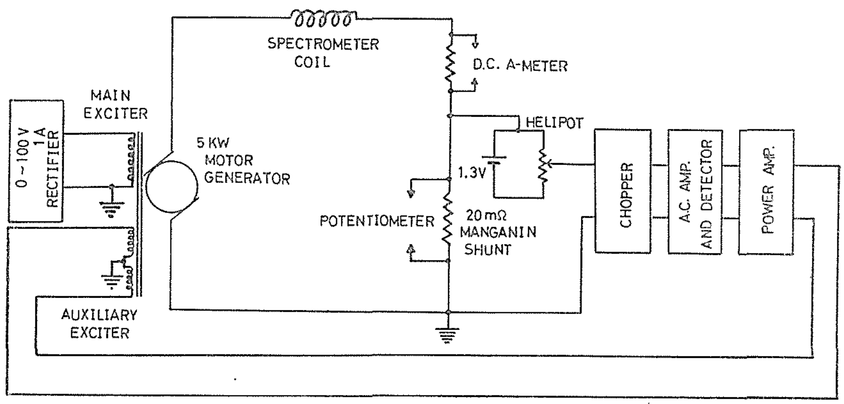

Fig. 3. Schematic diagram of the regulator system of the magnetic coil current.

duct of 2.5 m long to prevent the disturbance of the magnetic field due to the iron parts of the pump system.

III. 3. Stabilization of Magnetic Field

The magnet coil was excited by a 5 KW motor generater and its current was stabilized by an electronic system[9]. The block diagram of the system is illustrated in Fig. 3.

III. 4. Compensation of the Earth's Magnetic Field

Even a small component of the earth's magnetic field normal to the axis of the spectrometer will have a considerable effect on the transmitted beam of low energies. The conventional solution of this difficulty is to mount the spectrometer with its axis parallel to the earth's magnetic field, but this makes it very inconvenient to use the spectrometer as a detecting devise of radiations from nuclear reaction. Therefore, a pair of Helmholtz coils with 2 m height and 2 m radii surrounding the entire spectrometer was built. The coils provided an adequate compensating field which was uniform within 0.3 % in the area enough to cover the spectrometer.

IV. PERFORMANCE OF THE SPECTROMETER

The internal conversion lines of Cs^{137} and Co^{60} were used to examine the performance of this spectrometer. Evaporation residua of $Cs^{137}Cl$ and $Co^{60}Cl_2$ solutions were deposited on aluminium backings of 20 μ in thickness in a circular form of about 4 mm in diameter. The results are shown in Figs. 4 and 5.

The resolution obtained were as follows: 1.70% and 1.63% for the internal K and L conversion lines of 662 keV γ-ray from Cs^{137} respectively, and 1.76% and 1.69% for the internal conversion lines of the 1.17 MeV and 1.33 MeV γ-rays from Co^{60} respectively. These values are not so satisfactory as the calculated values listed in Table 2. The resolution depends upon the spherical aberration, the source diameter and thickness, the baffle size, lens inhomogeneities, goodness of the vacuum, scattering of electrons and other factors. In our case, main reasons of the deterioration of the resolution are as follows: (1) the finite source size, (2) the misalignment of the baffle system and (3) the mismatching of the magneitc axis and the mechanical axis of the cylinder. Particularly, the reason (3) may be the most important one, since the axis of the magnetic field was not actually measured. Also, some baffles might be desirable for the reduction of the number of secondary electrons due to γ irradiation and for the prevention of soft electrons from reaching the counter in a higher order focusing.

When the beam of electrons is focused by the magnetic field and the coil current is i amp, the electron momentum p is given by

$$p=ki.$$

In the above equation, k can be determined experimentally. The mean value of k for the Cs^{137} and Co^{60} conversion lines was estimated as 291.00 gauss cm/amp. This is within 1.2 % of the theoretical values.

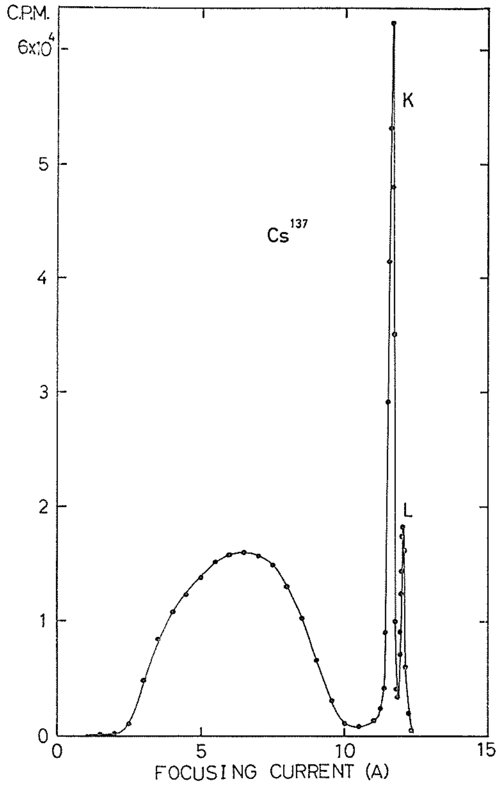

Fig. 4. Internal conversion spectrum of γ-rays in Cs^{137}.

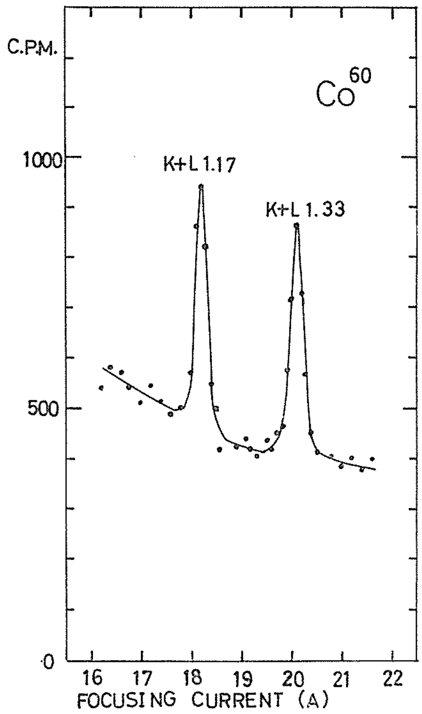

Fig. 5. Internal conversion spectrum of γ-rays in Co^{60}.

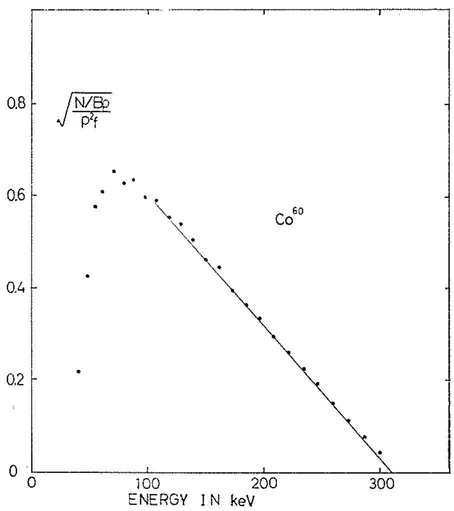

Fig. 6. Kurie plot of Co^{60} β-rays.

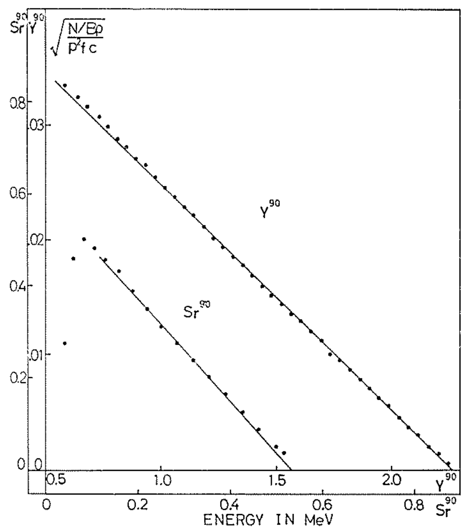

Fig. 7. Kurie plots of β-spectra obtained with composite Sr^{90}–Y^{90} source.

The β-ray spectra of Co^{60} and Sr^{90}–Y^{90} composite sources were also measured. The thickness of the aluminium backings and the method of the source preparations are the same as before. Kurie plot of the spectrum of Co^{60} agrees with that of the allowed transition[10] of the Fermi theory, while those of Sr^{90}–Y^{90} are interpreted by the unique first forbidden transitions[11]. The Kurie plots of these spectra are shown in Figs. 6 and 7.

The spectra of the low energy side (less than about 100 keV) deviate from straight lines. The deviation of the low energy part is considered to be the effect of the source thickness, radioactive impurity, back-scattering of aluminium backing, scattering and absorption effect of the detector window. The last effect seems to be predominant.

Improvements of the characteristics are now in progress, and larger transmission or better resolution will be obtained.

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