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A $\pi\sqrt{2}$ IRON-FREE MAGNETIC ELECTRON SPECTROMETER

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PREPARED BY AEROJET NUCLEAR COMPANY FOR
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
IDAHO OPERATIONS OFFICE UNDER CONTRACT E(10-1) -1375

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ABSTRACT

The Radioactivity and Decay Schemes group at the Idaho National Engineering Laboratory has constructed and operated a $\pi\sqrt{2}$, iron-free, magnetic electron spectrometer. This instrument is of the "Chalk River" design with three pairs of circular coils to produce the magnetic field. The optic circle radius is 35 cm. The diameters of the coils and their axial separations were chosen to produce the desired magnetic field. This spectrometer is capable of measuring electron and positron spectra up to ~ 3.3 MeV with a resolution (i.e., relative FWHM) variable from 1 to 0.01%. A PDP-8/E computer is used to operate and monitor the spectrometer. It is programmed to automatically set the current in the coils, monitor the current and control the counting intervals. The spectrometer is housed in a building constructed of nonmagnetic materials and is situated to minimize the magnetic interference from vehicular movements. The spectrometer has been used to measure the continuous electron and positron spectra from several isotopes as well as several conversion electron spectra.

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I. INTRODUCTION

The Radioactivity and Decay Schemes group at the Idaho National Engineering Laboratory (formerly the National Reactor Testing Station) has for over fifteen years carried out nuclear structure and applied nuclear studies by means of gamma-ray spectrometry. About ten years ago it was decided that it was necessary to extend this capability to include the study of both discrete (i.e., internal-conversion) and continuous electron and positron spectra from the radioactive decay process. In order to be able to carry out the desired studies of internal-conversion electrons, an iron-free magnetic spectrometer capable of high resolution and high precision was required. Also, since many of the sources would be made by neutron capture without isotope separation and therefore would be of low specific activity, a high luminosity instrument was desired. In this report we describe the design features and some operational characteristics of the instrument that we have constructed and operated for several years.

1. GENERAL DESIGN

Many types of magnetic electron spectrometers have been developed. The properties of several of these designs are described in the reviews by Siegbahn^[1] and Mladjenovic^[2]. The majority of the spectrometers constructed have been one of two types: the lens spectrometers and the "flat" spectrometers. The lens spectrometers are distinguished by the fact that the electrons travel generally along the magnetic field lines.

These instruments provide moderately high transmission which makes them good for coincidence experiments. They are generally limited in resolution. The "flat" spectrometers are characterized by the electron orbits which are basically perpendicular to the magnetic field lines. These instruments generally have higher resolution and lower transmission than the lenses.

The spectrometer which we have constructed is of the flat type. In this type of instrument, the magnetic field has both cylindrical symmetry and a plane of symmetry. It is convenient to describe the field in cylindrical coordinates (r, z, ϕ). The field is symmetric about the axis $r = 0$ and the plane $z = 0$. In such a field, the source and detector are generally placed in the symmetry plane ($z = 0$) at the same radius ($r = r_0$) as indicated in Figure 1. One electron orbit will then be the circle $r = r_0$; this is called the optic circle.

Fig. 1 Schematic view of electron orbits in a "flat" magnetic spectrometer. The radial deviation from the optic circle of a double-focusing spectrometer is shown by the solid area and the axial deviation by the bars.

For a magnetic field with this symmetry, the field near the optic circle is defined by the field in the symmetry plane $B_z(r, z=0)$, and it can be expressed by the series

$$B_z(r, 0) = B_0 \sum_{n=0}^{\infty} a_n \eta^n$$

where B_0 is the axial component (and the only component) on the optic circle, $\eta = \frac{r-r_0}{r_0}$ is the dimensionless radius parameter, and $a_0 = 1.0$.

In determining the desired values of the coefficients a_n , we are interested in what happens to electrons that are emitted in directions other than along the optic circle. Figure 1 illustrates electrons that are emitted with axial (i.e., in the direction of the Z axis) and radial divergence from the optic circle. The azimuthal angle (i.e., value of ϕ) after which these electrons return (1) to the radius r_0 for radial divergence and (2) to $z=0$ plane for axial divergence depends on the coefficient a_1 . In particular^[1,3] the focusing angles are

$$\phi_r = \pi/(1+a_1)^{1/2} \quad \text{and} \quad \phi_z = \pi/(-a_1)^{1/2}.$$

Simultaneous focusing in both directions (i.e., double focusing) can be obtained for a number of cases, the simplest of which is for $a_1 = -0.5$. In this case, double focusing is obtained at an angle of

$$\begin{aligned} \phi_r = \phi_z &= \pi/(\frac{1}{2})^{1/2} = \pi\sqrt{2} \text{ radians} \\ &= 254.56^\circ \end{aligned}$$

The orbits for this case are illustrated in Figure 1.

A number of $\pi\sqrt{2}$ double-focusing spectrometers have been constructed. The most complete discussion of the desired magnetic field shape has been given by Lee-Whiting and Taylor^[4]. The resolution of a spectrometer is related to the radial aberration; that is, the radial position $n(\phi)$ of the electrons at the focal plane, $\phi = \pi\sqrt{2}$. Given the value $a_1 = -0.5$, the dependence of the radial aberration on the source size and the accepted electron orbits is ^[4]

$$\begin{aligned} n(\pi\sqrt{2}) = & -h + \frac{1}{3} (1-8a_2)H^2 + \left(\frac{8}{3} a_2-1\right)T^2 \\ & + \frac{2}{3} (1-2a_2)h^2 + \left(\frac{4}{3} a_2-1\right)t^2 \end{aligned}$$

where

h = radial position of point on source,

t = axial position of point on source,

H = radial divergence of orbit from optic circle at the source, and

T = axial divergence of orbit from optic circle at the source;

By appropriate choice of a_2 any one of the last four terms in $n(\pi\sqrt{2})$ can be made zero. Lee-Whiting and Taylor^[4] give arguments leading to the conclusion that "the best transmission for given resolution, with a variable rectangular aperture, occurs when a_2 is either $1/8$ or $3/8$ ". The choice $a_2 = 1/8$ leads to a "wide-aperture" system and $a_2 = 3/8$ to a "high-aperture" spectrometer. Although comparable transmission could be obtained for either case, minor advantages exist for the $a_2 = 3/8$ case. Given the choices of $a_1 = -0.5$ and $a_2 = 3/8$, Lee-Whiting and Taylor^[4] determined the values of a_3 through a_6 which would give the best transmission.

The magnetic field that results from this calculation is very close to

$$B(r,0) = B_0/\sqrt{r}.$$

And it has been shown that for a field of this shape, electrons are focused quite well over a range of radii. Therefore, it is possible to place a series of detectors, or a photographic plate, in the focal plane and count electrons over a momentum range of $\sim 10\%$ with a minimal deterioration in the resolution.

It should be noted that for a magnetic field with the symmetry of interest here, the magnetic vector potential is entirely azimuthal, i.e., $A_r = 0$, $A_z = 0$ and $A_\phi = A(r,z)$. Then, from Reference 4, near the optic circle

$$rA_\phi = rA_0 + B_0 r^2 \sum_{m,n=0}^{\infty} C_{mn} \tau^m \eta^n$$

where A_0 is the vector potential at the origin and $\tau = z/r_0$. For the case of interest $C_{00} = 0$, $C_{01} = 1$ and $C_{mn} = 0$ for all odd m . The latter fact allows the vector potential to be written in terms of a singly indexed set of coefficients k_m where

$$k_m = (m-1)! C_{m-1,1} \text{ for odd } m, \text{ and}$$

$$k_m = m! C_{m,0} \text{ for even } m.$$

Note that $k_0 = 0$ and $k_1 = 1$.

2. Production of Magnetic Field

A number of double-focusing electron spectrometers have been built using iron magnets. Due to nonuniformity of the iron and its hysteresis, these spectrometers have limitations on the resolution, the low-energy performance, and the precision of the field shape. For a more precise field shape, it is necessary to generate the field in an iron-free environment with current carrying coils. Three basically different coil design have been used to generate this field shape. The first iron-free double-focusing spectrometer was constructed by Siegbahn and Edvarson^[5] and consisted of two concentric solenoids (i.e., approximations to current sheets) with an optic circle radius of 30 cm. This design has two free parameters, the ratios of the coil radii and currents. These values can be chosen so that the desired values of a_1 and a_2 can be obtained. Recently, a modified version of this spectrometer has been built^[6] in which each solenoid is split into two halves. This provides four free parameters and allows one to match the four coefficients a_1 - a_4 .

Another early coil design was that of Moussa and Bellicard^[7] which utilizes four pairs of circular coils (i.e., current loops). This design matched the field shape for the first two coefficients.

Based on the detailed analysis of Reference 4, a new coil design involving three pairs of current loops was developed. A 100-cm radius instrument of this type was constructed by Graham et al.^[8] at Chalk River. Later a 35-cm version was built by Wolfson et al.^[9] and very recently another 35-cm machine was built by Christmas and Cross^[10]. Detailed measurements of the radial aberrations have been made for the orbits in the 100-cm Chalk River instrument^[11]. The results are in excellent agreement with the calculated values. This illustrates one

of the important features of iron-free spectrometers; that is, their operational characteristics can be computed with a high degree of precision.

Because of the detailed design studies that were available and the excellent performance of the Chalk River instrument, it was decided to construct a spectrometer of this type at the INEL. Financial considerations limited the size of the instrument to one with an optic-circle radius of 35 cm.

The performance of an electron spectrometer is generally discussed in terms of its resolution, transmission and luminosity. For a group of monoenergetic electrons emitted by a source, the resolution R is the ratio of the observed line width (FWHM in momentum units) to the electron momentum. (This is usually expressed in percent.) The transmission T is the fraction of the monoenergetic electrons leaving the source that are counted at the peak of the line profile. The transmission is the product of two factors: (1) the fraction of the emitted electrons that reach the focal plane and (2) the fraction of the focused electrons that pass through a slit in front of the detector. (In Reference 2, these two factors are called the transmission and the acceptance factor, and our T is called the effective transmission.)

The luminosity L is the transmission times the source area, and is a measure of the counting rate for a source with a given decay rate per unit area. All three of these parameters depend on the spectrometer adjustments (e.g., baffle settings) and the source size. See References 1 and 2 for a general discussion of these quantities and the ranges of values expected for various types of spectrometers.

The following is a discussion of the INEL spectrometer in terms of its present configuration including recent upgrading of the computer control and monitoring system. The instrument is described in Section II and some performance results are given in Section III.

II. DESCRIPTION OF INSTRUMENT

1. GENERAL DESIGN

A schematic drawing of the components of the INEL electron spectrometer is shown in Figure 2 and a cut-away drawing is given in Figure 3. The magnetic field which focuses the electrons is generated by an electric current in three pairs of coils. The number of turns in each coil and the coil dimensions are the parameters used to match the desired magnetic field shape (see Section 2).

The electrons emitted by the radioactive source move in a vacuum which is provided by a tank and the necessary vacuum pumps. This tank includes external drive systems to vary the source orientation and the baffle and detector slit openings, and thereby the resolution and transmission (see Section 3).

The focused electrons are counted by a surface-barrier silicon detector which is operated either at room temperature or cooled with a dry ice and alcohol mixture. The pulses from the detector are amplified and all those above a discriminator threshold are counted.

As indicated in Figure 2, the current in the spectrometer coils is supplied by a power supply which is computer controlled. The computer allows the count rate to be measured at a sequence of current values with various current step sizes and counting durations. The stability of the current in the coils is measured by means of a

digital voltmeter. The input to and output from the computer are via teleprinter, cassette tape and/or plotter.

The power dissipated in the spectrometer coils is removed by demineralized water flowing through the coils. The temperatures of the coils are monitored and recorded at regular intervals.

Fig. 2 Schematic presentation of the various components of the INEL electron spectrometer and their relationships.

Since, for precise measurements, an iron-free spectrometer needs a low magnetic background, this whole system is housed in a building which is constructed of wood, aluminum and nonreinforced concrete. The spectrometer itself is surrounded by three sets of current-carrying coils which cancel the three components of the local magnetic field (from the earth and equipment in the building). The building includes its own heating and cooling system.

Fig.3 Cutaway drawing of spectrometer including the coils, their support castings and the vacuum tank.

The specifications for the components of this system were generated from the basic goals of being able to measure electron energies to about 1 part in 10^5 (neglecting calibration error contributions) and providing an ultimate resolution of 1 part in 10^4 .

The remainder of Section II deals with more detailed descriptions of these components.

2. SPECTROMETER COILS

2.1 General Features

In Reference 4 it was found convenient to describe the magnetic field shape in terms of the expansion coefficients k_m of the vector potential. The first five expansion coefficients of the vector potential from the Lee-Whiting optimization ^[4] are given in Table I. (The coefficient k_1 is a normalization constant and is taken to be 1.00). As an aid in specifying manufacturing tolerances, Lee-Whiting and Taylor^[4] have computed tolerances Δk_m such that, if only the one k value were in error by this amount, there would be a line broadening of about 25% at a resolution of 0.01% (the best resolution expected). These Δk_m are also given in Table I. From these Δk_m values, Lee-Whiting and Taylor^[4] also estimated the effect of various manufacturing errors such as (1) the differences in radii of two similar coils, (2) vertical displacement of one coil, (3) tilt of a coil and (4) elliptical distortion of a coil. This information was used in the generation of the coil manufacturing and assembly tolerances.

The general design of the coils is somewhat different from that of the other instruments of this $\pi\sqrt{2}$ type^[8-10]. Other spectrometers

have used coils wound of aluminum or copper ribbon. These conductors are cooled through the edge of the ribbon. The power is supplied to these coil systems at high voltage (~ 500 volts) and low currents, namely, 20 or 40 A to focus 2.5 or 4 MeV electrons. In contrast, the INEL spectrometer is built to operate at low voltages (up to only 80 V) and high currents, namely, up to 200 A to focus 3.5 MeV electrons. The conductors are square copper bars with an internal hole for the coolant. A disadvantage of the INEL design in matching the desired coefficients k_m is that the ratio of the number of turns in the various coils cannot be varied by small amounts. However, it was determined that satisfactory ratios could be found.

TABLE I

Expansion Coefficients for Vector Potential of Magnetic Field
Optimum Values for $\pi\sqrt{2}$ Spectrometer
And Values Computed for INEL Spectrometer

m	Optimum Field ^a		INEL Spectrometer	
	k_m	Δk_m^b	k_m^c	$\frac{\delta k_m^c}{\Delta k_m^c}$
1	+1.0000	---	+1.0000	----
2	+0.5000	0.0013	0.50003	0.02
3	-0.2500	0.0033	-0.24981	0.06
4	-0.5417	0.15	-0.5429	0.01
5	+0.927	2.2	0.929	0.001

^aFrom Reference 4.

^bTolerance such that if k_m is in error by Δk_m , line is broadened 25% at resolution of 0.01%. The signs given in Reference 4 have been omitted.

^cComputed for final coil parameters given in Table IV.

$$\delta k_m = |k_m (\text{optimum}) - k (\text{INEL})|.$$

After an initial design of these coils was completed, the coefficients of the magnetic vector potential were computed, including corrections for the finite coil sizes^[12]. The derivatives of the k_m with respect to the coil radii and axial separations were also generated. These data were used to provide final design dimensions. A portion of the specifications for the construction of the coils is given in Table II.

A typical cross section of each size coil is shown in Figure 4. As indicated, the coils consist of sections, or "pancakes", each with two layers of turns. Figure 5 is a view of a small coil pancake which

Fig. 4 Cross sections of the three sizes of coils. The section of the large coil is taken through the region of the electrical connections. The other sections are at a point 180° from the electrical connections. At all other angular positions the turns of the top and bottom layers will not be in line. (See, e.g., Figure 5.)

TABLE II

PORTION OF THE SPECIFICATIONS FOR COIL CONSTRUCTION

Dimensions - assembled coil (inches)

	<u>Large Coils</u>	<u>Medium Coils</u>	<u>Small Coils</u>
1. mean coil radius - design value	27.046	13.322	6.207
2. maximum deviation of mean coil radius from design value	±0.080	±0.040	±0.040
3. Maximum difference in mean coil radii	0.012	0.008	0.015
4. mean coil radii determined within	±0.005	±0.004	±0.004
5. vertical center of coil determined to	±0.002	±0.005	±0.005
6. coil top, coil bottom and ring plates flat and parallel within	0.002	0.002	0.002
7. maximum deviation of coil enclosure and coil alignment rings from circularity	±0.002	±0.002	±0.002
8. radius $r_j(\theta_j)$ of each layer determined within	±0.003	±0.002	±0.002
9. radius $\bar{r}(\theta_j)$ of each layer determined within	±0.003	±0.002	±0.002
10. mean layer radius $\bar{r}$ determined within	±0.005	±0.004	±0.004

Electrical - assembled coil

11. maximum current (D.C. amps)	200	200	200
12. maximum voltage across a coil (volts)	25	4	1
13. resistance of a coil (ohms)	0.12	0.02	0.005
14. maximum power dissipated (watts) per coil	5000	800	200

General

15. magnetic permeability of all materials	1.0000 ± 0.0005		
16. number of pancakes per coil	4	3	2
17. number of layers per pancake	2	2	2
18. number of turns per layer	11	6	5

has been sectioned. This coil winding configuration places the electrical and water connections on the outside of the pancake where they are accessible. The conductor is 0.345-inch square copper with a 0.203-inch diameter central hole. There are two features of this configuration that differ from those assumed in the Lee-Whiting calculations^[4]. First, the current paths are spirals instead of circles (i.e., there is a radial component to the current in addition to the desired azimuthal component). Order of magnitude estimates^[12] indicate that, since the radial components of the current

Fig.5 Section of a small coil pancake showing the turns in each layer. The crossover region between the layers is in the notch in the alignment ring (in foreground).

in the two layers of a pancake are in opposite directions, the net magnetic field from these components will be negligible. Second, there are connectors between layers at the inside of each pancake and at the outside between pancakes where the current is axial. This perturbation is also expected to be negligible.

2.2 Coil Construction

The fabrication and assembly of the spectrometer coils were carried out at the Y-12 facility of Union Carbide Corp., Oak Ridge, Tennessee. The process of winding a large pancake is shown in Figure 6. The windings were permanently mounted on a brass alignment ring, as shown in Figures 5 and 6. During the winding process, this

Fig.6 View of large pancake being wound.

ring was constrained by a large steel plate (see Figure 6). In addition to the formvar insulation on the conductor, a layer of epoxy impregnated tape was placed between each turn. Also, a layer of impregnated cloth was placed between the layers. After the winding was completed, the electrical connections were soldered to each layer. Nonconducting dowel pins were then placed axially through the electrical connectors on the two layers of a pancake to reduce the possibility of a pancake unwinding. The epoxy was then cured at $\sim 160^{\circ}\text{F}$.

Extensive tests indicated no electrical shorts between the turns or to the alignment rings. Measurements of water flow rates showed that there were no constrictions of the central holes.

In order to match the desired magnetic field shape, it was necessary to accurately determine the average current position in each pancake. Then the pancakes could be assembled into coils in such a way as to minimize the difference between the two coil radii. This need was met in four steps. First, before any piece of conductor was used, it was x-rayed at regular intervals (i.e., 3 feet, 4 feet and 10 feet, respectively, for the small, medium or large pancakes) to determine the position of the central hole. These measurements were made in the two perpendicular directions. After some practice in reading the x-rays, the hole position was determined to ~ 0.001 inch. If the wall thickness varied by ≥ 0.007 inch over the shorter of (1) the length needed for a pancake or (2) 150 feet, the conductor was not used. The wall-thickness measurements were then used to compute the mean current position relative the outer edges of the conductor. The orientation of the conductor had to be maintained between the x-ray measurements and the pancake winding.

Fig 7 Large coil in place to be x-rayed to determine radial positions of turns.

Second, maintaining the necessary radial tolerances involved careful coil winding. During the process of winding, the outer radius of each turn was measured at six angles as it was wound. These radii were continually adjusted to match, as nearly as possible, the design values. This procedure minimized the variation in the mean pancake radii.

Third, an x-ray measurement of the position of each turn in the pancake was made after the epoxy had set. As shown in Figure 7, these measurements were made with the x-ray source several feet above the plane of the pancake to minimize the angular divergence of the x-ray beam. These x-rays were taken at six angular positions and from both sides of the pancake (i.e., twelve pictures). Useful data were obtained only for the layer closest to the x-ray film. (For the large pancakes, two pictures were taken at each angle with different radial positions.) From these x-rays, the positions of the inner and outer edges of each turn were determined at each of the six angles. The distances were measured with respect to the inside edge of the alignment ring (which is a circle). The diameter of this edge was determined by separate measurements. From all of these numbers the mean current radius was determined for each pancake.

Since the alignment rings were quite susceptible to distortion before the coils were wound and cured they were handled with great care. Also, these and all other dimensional measurements were made at known temperatures, and generally in a temperature controlled environment, in order to minimize any changes due to temperature variations.

Fourth, the pancakes were selected and arranged. Fortunately, the coils for two identical spectrometers were constructed at the same time. Also, two spare pancakes of each size were wound. Therefore, 18 large pancakes were wound. It was then possible to choose 8 of the large pancakes with the smallest radii for one spectrometer and eight with the largest radii for the second. The radii of the pancakes and the assembled coils for the INEL spectrometer are given in Table III. These radii have all been corrected for the position of

TABLE III

Pancake and Coil Radii

Coil		Pancake Number	Pancake Radii (inches)		Coil Radii (inches)	
Size	Position		Mean	Range	Mean	Difference Between Pair
large	top	05	27.0609			
		14	27.0584			
		10	27.0598			
		20	27.0587	0.0025	27.0595	
	bottom	06	27.0594			
		16	27.0590			
		04	27.0603			
		11	27.0586	0.0017	27.0593	0.0002
medium	top	08	13.3325			
		03	13.3305			
		05	13.3281	0.0044	13.3304	
	bottom	07	13.3330			
		10	13.3290			
		01	13.3280	0.0050	13.3300	0.0004
small	top	06	6.2058			
		09	6.2049	0.0009	6.2054	
	bottom	02	6.2035			
		04	6.2071	0.0036	6.2053	0.0001

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Fig.9 Bottom half of spectrometer coil system in place on support stand.

the total current I_t since there is also a small radial component. The differences between I_ϕ and I_t are 2, 9 and 43 parts in 10^6 for the large, medium and small coils, respectively, and are therefore negligible. Second, the final k_m values in Table I are for an optic circle radius of 35.07 cm. The difference δk_m between the optimum k_m are given in units of the tolerances Δk_m . The main effect of using $r_0=35.07$ cm is that $\delta k_5=0.001 \Delta k_5$ instead of the value $0.2 \Delta k_5$ which is obtained with $r_0=35.00$ cm.

As shown in Table I, the calculated k_m values agree well with the optimum values. This agreement (i.e., all $\delta k_m/\Delta k_m \leq 0.06$) is in fact

TABLE IV
Mean Radii and Half-Separations of
Assembled Spectrometer Coils

<u>Coil</u>	<u>Radius</u>		<u>Half-Separation</u>	
	<u>(inches)</u>	<u>(r_o)^a</u>	<u>(inches)</u>	<u>(r_o)^a</u>
large	27.0594	1.96150	9.1235	0.66135
medium	13.3302	0.96629	10.7403	0.77855
small	6.2053	0.44981	1.7140	0.12425

^a

Value relative to optic circle radius of 13.807 inches.

somewhat misleading since the uncertainties in these k_m have not been computed. A crude estimate of the uncertainties can be obtained from the fact that a symmetrical increase in the axial separation of the large coils by 0.002 inch will change both k_2 and k_3 by $\sim 0.1 \Delta k_m$. Since this change is the magnitude of the precision of the construction, any agreement to better than $\sim 0.1 \Delta k_m$ is meaningless.

3. VACUUM SYSTEM

The vacuum system consists of the tank and its associated mechanical assemblies and the pumping system. The main portion of the vacuum tank is shown in Figure 10. This section was constructed at the Y-12 facility of Union Carbide Corporation, Oak Ridge, Tennessee, and is made of welded aluminum plate. A section of the tank is shown in Figure 11.

Fig.10 Main portion of vacuum tank and one 6-inch valve.

3.1 Vacuum Tank

The tank is supported in the spectrometer by the castings for the small and medium coils. Shims below the tank and on top of the lower medium coil casting provide the axial position desired. Radially the tank fits snugly around the small coil support castings. As shown in Figure 11, the tank only comes half way around the castings; it is held in place by straps which wrap the rest of the way around the casting.

Fig. 11. Section of vacuum tank showing valves on each end and indicating the source and detector positions.

3.2 Baffle

The vacuum tank supports three mechanical systems: baffles, source chamber and detector chamber. The original adjustable baffles which allow control of the resolution and transmission are shown in Figure 12. (The current system includes teflon guide blocks.) These baffles are curved to fit the calculated curves shown in Figure 13. The baffles are adjusted in the radial direction by the direct motion of the rod shown in Figure 12 via an external screw drive. Soldered bellows are used for the vacuum seals on the moving rods and O-rings on the static parts. This drive system is adequate since exact

Fig 12 Original baffle system to define resolution and transmission. Baffles are at angle of 78° from source. (See Figure 11.)

reproducibility has not been needed and a small degree of tilt in the baffle edge is acceptable at all but the highest resolution. These baffles are mounted at an angle of 78° from the source as shown in Figure 11.

Gamma rays and high-energy electrons can go through the baffle opening and strike the vacuum tank about midway between the source and detector. Therefore, at times a secondary, fixed baffle has been placed at an angle of 78° from the detector in order to stop the secondary or scattered electrons.

3.3 Source and Detector Chambers

A 6-inch gate valve (see Figure 9) is mounted on each end of the tank. The source and detector chambers are mounted on these valves.

Fig 13 Computed extent of electron beam at baffle plane for various radial aberration values, or resolutions, at the focal plane. The resolution values shown are for a point (zero-area) source. For actual sources (of optimum size), the resolution will be larger by a factor of about 1.7.

The chambers, valves and tank end plates are all aligned by dowel pins to maximize the position reproducibility after disassembly. This is important since the source chamber is removed in order to introduce a source. O-ring vacuum seals are used.

The electron detector chamber includes two surface-barrier Si detectors. One views the focused electrons and the other is completely enclosed and monitors the background (i.e., cosmic rays, local radio-activity and gamma rays from the source). These detectors are 0.5 mm thick by 300 mm² in area and are operated either at room temperature (resolution $\approx$ 28 keV) or cooled with a dry-ice and alcohol mixture (resolution $\approx$ 7 keV). The beam of electrons counted is defined by a pair of straight-edged slit jaws. The slit width can be varied externally by directly driving one slit jaw with a screw-driven bellows-sealed rod. (Since only one jaw is moved, the effective optic circle radius changes with the slit width.) The slit jaw is driven so that it does not tend to tilt, but there is lash in the screw drive.

TABLE V

Nominal Dependence of Spectrometer Resolution on Source Width, Baffle Setting and Detector Slit

<u>Source Width (inches)</u>	<u>Total Baffle Opening (inches)</u>	<u>Detector Slit Width (inches)</u>	<u>Resolution (%)</u>
0.004	0.6	0.004	0.010
0.04	1.7	0.04	0.10
0.4	5.4	0.4	1.0

This means that measurements which require the same slit width must be run consecutively. Table V gives the nominal dependence of the spectrometer resolution on source width, baffle setting and detector slit width.

Any source chamber must allow for alignment of the line source with the magnetic field and adjustment of the source-detector focusing angle. (The Chalk River instrument^[8] also allows adjustment of the source radius. However, since this magnetic field shape allows focusing over a large range of the focal plane, this is believed to be of

Fig.14 View of complete spectrometer with original source and detector chambers. A source is shown in place. This source chamber has a minimum of scattering material behind the source. The detector chamber includes only one detector and is only for room temperature operation.

secondary importance.) Two source chambers have been used. The first one appears in Figure 14 and contains a minimum of material behind the source. The two adjustments are made by rotating different sections of the complete chamber. (These adjustments are difficult to make with the chamber evacuated). O-ring seals are used between the various sections.

The second source chamber has the source mounted on a carriage system. This carriage can be rotated and driven along the optic circle by external micrometer drive rods. This system provides easy adjustment, but there is much more scattering material behind and near to the source.

3.4 Pumping System

The vacuum system includes a 6-inch diameter oil diffusion pump (CVC-PMCS-6B) shown in Figure 15. This pump is ~ 5 feet below the spectrometer and is connected through an 8-inch diameter pumping line (with 6-inch diameter sections at each end). A water-cooled baffle sets on top of the diffusion pump. The valves to allow rough pumping of the vacuum tank are driven by compressed air and are solenoid controlled. They are operated from the main control room. The backing pump (Welch-1397) is located about 12 feet away. With a recently pumped system, the pressure in the tank can be reduced from atmospheric to 10^{-5} torr in less than 15 minutes. A pressure of $\approx 10^{-6}$ torr is generally obtained. The pressure can be monitored near the diffusion pump or near the tank with ion gauges, in addition to the thermocouples which observe the roughing pump operation.

Since the diffusion and mechanical pumps both contain steel, care had to be taken not to distort the magnetic field of the spectrometer.

Fig.15 Diffusion pump and associated components of vacuum system. The water-cooled baffle, valves and pumping lines to tank and mechanical pump are shown. Portions of the local magnetic field cancellation system are shown.

Before the spectrometer coils were installed, the pumps were put in place. No DC or low frequency AC fields, or changes in fields, were observed at or near the spectrometer location from the pumps or movement of the pumps. (Measurements had a sensitivity of ~ 0.01 milligauss.)

A small mechanical pump can be connected to either the source or detector chamber by means of a flexible hose. This pump is used to pump down a chamber after it has been opened. This minimized the transfer of air into the main vacuum tank when the gate valve is opened.

4. ELECTRON COUNTING SYSTEM

The focused electrons are detected by a surface-barrier silicon detector which is mounted close behind a pair of slit jaws. The detector is 0.5 mm deep and 300 mm² in area. The first stage of the preamplifier is mounted in the chamber. When the detector is cooled (to dry ice and alcohol temperature), these components are also cooled.

The rest of the preamplifier is about two feet away. The signals then go to an amplifier (Tennelec TC-202) and a discriminator (Ortec 429). Those pulses above the discriminator level are shaped and counted by a scaler in the computer system. The presence of the discriminator means that some electron-produced pulses will be rejected. Therefore, it is necessary to determine the counting efficiency for all electron energies (or spectrometer currents) of interest. This efficiency will also depend on the detector temperature.

In order to monitor the background counting rate (from natural or other radioactivity outside the spectrometer and from the gamma rays from the source), a second detector is mounted in the source chamber. It is completely shielded from electrons entering via the detector slit, but is otherwise similar to the first detector. The electronics are similar to those of the other detector.

5. CURRENT SUPPLY

The current to the spectrometer coils is provided by a commercially obtained supply (Mekel Associates) which delivers up to 200 A (at up to 80 volts). At 200 A, the spectrometer will focus electrons of about 3.5 MeV. This current supply presented a number of challenging design problems. The control circuitry shown as a block diagram

in Figure 16 utilizes two stages of series regulation. The desired current range (up to 12.5, 25, 50, 100 or 200 A) is selected by changing the value of the current sensing resistor. Within a given current range the desired magnet current may be selected under computer control by a 17-bit relay-operated voltage divider which is included in the feedback loop of the second regulator stage. Table VI gives the minimum current step size and some corresponding energy increments for each of the current ranges.

Fig. 16 Block diagram of current supply

TABLE VI
Minimum Current and Energy Steps on
Various Current Ranges

Range Setting	Maximum Current (A)	Minimum Current Step (mA)	Typical Values		
			Current (A)	Energy (keV)	Minimum Energy Step (keV)
1	12.5	0.095	10	35	0.0006
2	25	0.19	10	35	0.0013
			15	75	0.0017
			20	125	0.0021
			25	185	0.0025
3	50	0.38	25	185	0.005
			40	400	0.006
			50	560	0.006
4	100	0.76	50	560	0.012
			75	1000	0.013
			100	1450	0.014
5	200	1.53	50	560	0.025
			100	1450	0.028

All components which effect stability of the current supply output are operated in a temperature-controlled environment. The design requirement for stability of this supply was 1 part in 10^5 over an eight-hour time period. The major source of instability in the supply during initial operation was determined to be due to excessive changes in thermal EMF generated in relay contact materials. Special relays, employing low thermal EMF materials were installed to correct this problem.

The spectrometer current can be monitored either manually or automatically by passing the current through a resistor in series with the spectrometer coils. This series resistor can have a value of

1, 2, 4, 8 or 16 m Ω . These resistors are contained in a circulating oil bath which is heated to a constant 27⁰C. The resistors are made of manganin which has a small change in resistance with temperature; also the bath temperature is approximately at the point at which the resistance change with temperature is zero. Manual current monitoring is done with a 6-digit potentiometer (Guideline Instruments 9160) and associated components, while automatic monitoring is done with a 5-digit digital voltmeter (Fluke 8300A).

6. CONTROL AND MONITOR BY COMPUTER

The control of various spectrometer operations is carried out with a PDP-8/E computer with an 8K memory of 12-bit words. The computer functions are illustrated in Figure 17. The input to the computer is via the cassette tape unit for programs, the teleprinter for information needed to set up the measurements and the computer switch registers for various options available during the measurements.

In the measurement of the electron spectra, the computer carries out two main functions: (1) control of the current supply and (2) operation of the count scalars. Given the current range setting of the supply, any desired current is obtained by having the computer set the relay-operated voltage divider (ROVD) to the proper value. The computer is actually programmed to allow one to set up as many as twenty consecutive runs. Each run consists of those counts taken at equally spaced current values and for equal counting times. For example, the spectrum of a conversion-electron line shown in Figure 18 consists of five runs. The computer program, through the associated interfaces, also starts, stops and clears the scalars recording the counts from the electron and background detectors.

Fig. 17 Schematic drawing of the various functions of the computer which controls and monitors the spectrometer.

Fig. 18 K internal-conversion line from 1002-keV gamma ray from decay of ^{182}Ta . Note change in scale of the current axis. The five runs used to accumulate these data are indicated by the various point symbols.

This control program has numerous features to increase its flexibility. The computer switches can be used to halt the program at the end of any count (or any run). The program can then repeat the last count (or run) or continue to the next count (or run). At any point, the program sequence can be interrupted and the input information (e.g., count times, start-of-run and end-of-run current values) for subsequent runs can be updated on the basis of the accumulated information.

The spectral information can be presented in three forms. It is usually stored on the cassette tape. The data can also be printed on the teleprinter and/or plotted on the x-y plotter. In addition to the whole set of data, the user can select any subset of runs to be printed or plotted. The log of the number of counts is plotted vs. the current. For each run a different scaling factor can be used on the current axis (i.e., different amps/mm). Therefore, the point spacing in Figure 18 could be duplicated (but only one plot symbol is available). The spectral data can be transferred from the cassette tape to IBM 360/75 compatible tape via a program on a PDP-9 computer.

As indicated in Figure 17, the computer also carries out two monitoring functions. First, it measures the temperatures at several points in the system. These points are listed in Table VII and include the hot ends of all eleven coil cooling paths (see Section 7). These values are measured every minute as long as the computer is running and independent of whether data are being accumulated. About every 15 minutes the temperature data are recorded for subsequent print out. Any time that the temperature for any sampling point is 9.7°C above a nominal 22°C , the current supply is turned off. It can then be restarted only manually. The temperatures are measured by means of thermistors which are switched into a bridge circuit to provide a temperature. Temperature changes as small as $\pm 0.01^{\circ}\text{C}$ are recorded, but the accuracy is only about 0.5°C .

The computer also monitors the current in the spectrometer coils by measuring the voltage across the series resistor. This measurement is made several times (the number is an input parameter) during each count. The output includes the average value and the total range of

TABLE VII
Temperature Monitor Points

Number	
1	Hot end of top pancake of top large coil
2	Hot end of 2nd pancake of top large coil
3	Hot end of 3rd pancake of top large coil
4	Hot end of bottom pancake of top large coil
5	Hot end of top pancake of bottom large coil
6	Hot end of 2nd pancake of bottom large coil
7	Hot end of 3rd pancake of bottom large coil
8	Hot end of bottom pancake of bottom large coil
9	Hot end of top medium coil (all three pancakes in series)
10	Hot end of small coils (all four pancakes of both coils in series)
11	Hot end of bottom medium coil (all three pancakes in series)
12	Vacuum tank
13	Water inlet line
14	Blank
15	Blank
16	Reference resistor

the values. The information on the spread of currents is useful for determining the long-term degeneration of the current supply in order to determine when it needs retuning or repair.

7. COIL COOLING SYSTEM

Figure 19 shows a schematic drawing of the coil cooling system. The cooling is provided by demineralized water which is pumped through the eleven indicated cooling paths. As noted in the previous section (Table VII), the temperature is monitored at the hot end of each cooling path as well as on the inlet water line.

Fig. 19 Schematic drawing of coil cooling system.

As indicated in Figure 19, the heat is removed from the demineralized water in a heat exchanger. The secondary fluid is the local "fire" water which is dumped after a single pass through the exchanger. By controlling the volume of flow on the secondary side, the temperature of the primary water coming out of the heat exchanger is controlled to $<1^{\circ}\text{C}$.

Typically the primary cooling system is run at a pressure of 50 to 100 psi at the gauge just above the pump. This provides a flow rate of a few gallons per minute. The temperature rises in the coils under these conditions are discussed in Section III.3.

About 1% of the primary flow out of the heat exchanger is passed through a mixed-bed ion exchange column. This allows the water resistivity to be maintained at > 1 megohm-cm.

The cooling water is delivered to the spectrometer through high-electrical-resistance hoses which have an area of $\sim 1 \text{ cm}^2$ and length of ~ 1 meter. These water paths do provide routes for the electric current to by-pass the spectrometer coils. However, since the total coil resistance is $\sim 0.3 \Omega$ and the water resistance is $\sim 10^6 \Omega$ through each hose, less than 1 part in 10^6 of the current should by-pass the coils. This leakage current fraction should be independent of the current value and, therefore, should not affect the measurement of electron energies.

8. MAGNETIC FIELD CANCELLATION SYSTEM

Iron-free $\pi\sqrt{2}$ spectrometers are generally operated on the assumption that the electron momentum is proportional to the electric current in the coils. (That is, electron energies are determined from the coil current and not from magnetic field measurements). This means that

magnetic fields from all other sources must be reduced to a negligible level. Such extra magnetic fields would also perburb the focusing characteristics and thereby degrade the resolution.

Therefore, three sets of current-carrying coils have been installed in the building in order to cancel the three components of the local magnetic field. The vertical component is cancelled by two pairs of square coils. The east-west and north-south components are each cancelled by one pair of square coils.

The design of these coils was based on the calculations of Lee-Whiting.^[13] The parameters of the actual coils are given in Table VIII. After installation, the positions of the individual coils were adjusted to optimize the magnetic field cancellation. These adjustments were necessary to compensate for the iron in the equipment (especially the heating and cooling system) within the building.

TABLE VIII

Parameters of Magnetic Cancellation Coil System
(All coils are square and are in pairs)

<u>Field Component</u>	<u>Length of Edge (feet)</u>	<u>Separation (feet)</u>	<u>Wire Gauge</u>	<u>No.of Turns</u>	<u>Nominal Current (A)</u>
vertical - outer pair	19½	19½	10	85	1.8
inner pair	19½	6⅔	10	51	1.8
north-south	18½	9	15	40	1.6
east-west	18½	10	15	1	1.5

The currents to these coils were supplied by current-regulated supplies (Kepco KS 60-5M, KS 60-2M and ABC 7.5-2M). There is no automatic monitoring of the residual field or use of the residual field to control the current supplies. Results of mapping the residual field are given in Section III.4.

The local magnetic field and the residual fields are measured with a dual probe magnetometer. These probes can be operated to measure the field at one point, or the difference in the fields at two points.

9. BUILDING

In order to minimize the interference with the magnetic field of the spectrometer, the building constructed to house it was built of wood, aluminum and nonreinforced concrete. The building is about 20 feet by 40 feet in area and about 20 feet high. The building is ~ 300 feet from the nearest permanent building (the Advanced Test Reactor, ATR) and ~ 200 feet from the nearest road. This distance is necessary to eliminate any magnetic effects from the movement of large trucks associated with the reactor operation. A plan of this facility is shown in Figure 20.

The building contains its own heating and cooling system. The temperature control is via thermostats in the spectrometer room and the room below the spectrometer. The water is supplied from the ATR and the drain returns there. A sink and drain are provided for decontamination of items with low-level radioactivity.

The particular site chosen was based primarily on the availability of space at a sufficient distance from traffic of large trucks. Before the construction was begun, a magnetic survey of the area was made and no anomalies were found. Surveys were made during the construction to assure that no significant magnetic materials were used in the structure.

Fig. 20 Building floor plan - main floor

Fig. 20 Building floor plan - basement

III. PERFORMANCE

1. TEMPERATURE DEPENDENCE OF SPECTROMETER CALIBRATION

In order to determine the degree of temperature control needed for the spectrometer coils or the building, it is necessary to have a quantitative estimate of the change in the spectrometer calibration with temperature. The change in the calibration results from (1) the change in the diameter of the coils, (2) change in axial spacing of the coils and (3) the change in the radial position of the source and detector. The theoretical basis of such a calculation is given in Appendix II of Reference 8. Calculations of the temperature dependence of the calibration constant are given in References 8 and 9 for two other spectrometers of this type.

The results of a calculation of the temperature dependence of the calibration constant of this spectrometer are given in Table IX. These computations assume that each component (i.e., coils and alignment ring, tank and support casting) is free to expand without restraint. While this may be a good assumption in the case of a uniform change of the building temperature over a long time, it will not be the case over the short term or for heating of the coils. The tendency of the coils to expand will be slowed by their bonding to the alignment rings which may be at a lower temperature. The change in the axial coil separations will depend in the short term on the expansion of the coils themselves, but in the long terms on the expansion of the support castings. In spite of these problems, the values in Table IX do indicate that if precise energy comparisons are to be made, the temperatures must be controlled within a few degrees C. However, for measurements other than precise energies, long-term drifts of several degrees should not be significant.

TABLE IX

Temperature Dependence of Calibration Constant

The changes in the calibration constant ($\Delta B_p/B_p$) are computed from the information in References 4 and 8 for the materials used in this spectrometer.

Change	$\frac{\Delta B_p}{B_p} \times 10^6$
1. 1°C rise for coils, tank, supports	-0.97
2. 1°C rise for coils only	2.3
3. 1°C rise for tank and supports	-3.2
4. rise for coils 3°C - large, 2°C - medium, 0.9°C - small; none for supports and tank	-4.5
5. as #4 plus 1°C rise in supports and tank	-5.7

2. BUILDING TEMPERATURE

Over a period of years, the building air temperature has been constant within $\sim 3^\circ\text{C}$ excluding those periods when the temperature control system was not operating. For a period of several weeks the temperature changes in the area of the spectrometer were measured with a sensitive thermistor system. No short-term (minutes) oscillations were observed. For two-day periods, the smallest and largest total temperature spreads were $1/3^\circ\text{C}$ and 1°C . For six-day periods, the smallest and largest spreads were $2/3^\circ\text{C}$ and 1°C . As indicated in Table IX for a uniform temperature change of all components this corresponds to a variation in the calibration constant ≤ 3 parts in 10^6 . (Since the spectrometer coils contain ~ 3000 pounds of material, their temperature variations will be somewhat slower and somewhat smaller than the air temperature changes.)

3. COIL TEMPERATURE

Electron spectra have been collected over the last few years with the coil cooling system operated in three different ways. First, for measurements below 300 keV, it has been common to run the spectrometer with no cooling water. Coil temperature rises of a few degrees are observed.

The second mode of operation is that described in Section II.7. Here the inlet water temperature is constant and the outlet temperatures vary with the spectrometer current. Typical temperature rises are shown in Table X. These values were obtained with the same pressure drop across each of the cooling paths. Each cooling path has a valve which allows the flow rate to be varied. In principal, these adjustments could be used in conjunction with the calculations in Section 1 to obtain relative coil-temperature rises that would result in no change in the calibration constant. (This is possible since items 2 and 4 in Table IX have opposite signs.) This technique has not been used, however.

From the values in Table X, it appears that the shifts in the calibration constant are generally less than 2 parts in 10^5 over large energy ranges and less than 1 part in 10^5 over small ranges. With the exception of measurements of very precise energies, these changes are insignificant.

The third method of operating the cooling system is based on the fact that the secondary water temperature is quite constant. Therefore, it is feasible at times to operate without any control of the primary water inlet temperature. This is a reasonable choice for measurements

TABLE X

Coil Temperature Increases

Measured values of temperature difference between hot end of cooling path and inlet water for various water pressures and coil currents.

Current (A)	Pressure (psi)	Temperature Difference (C ⁰)				Vacuum ^c Tank
		Coil				
		Large #1 ^a	Large #2 ^a	Medium ^b	Small	
150	120	5.2	4.9	3.4	1.9	1.7
	100	5.6	5.3	4.2	2.3	1.9
	80	6.5	6.1	4.4	2.6	2.3
100	120	2.5	2.4	1.9	1.0	1.6
	100	2.6	2.5	1.9	1.1	2.2
	80	2.6	2.5	2.1	1.2	2.0
	60	3.2	3.1	2.4	1.4	1.9
75	80	1.4	1.3	0.9	0.5	0.0
	60	1.7	1.6	1.2	0.7	0.3
	40	2.3	2.2	1.7	0.9	0.8
50	60	0.8	0.8	0.7	0.4	0.6
	40	0.9	0.9	0.7	0.4	0.5

^a Average value for four large pancake cooling paths.

^b Average value for two medium pancake cooling paths.

^c Since the vacuum tank is not intimately coupled to the heat source, these values depend somewhat on the current-pressure history as well as the indicated values.

at relatively poor resolution (i.e., $R \geq 0.1\%$) and at high energy (e.g., all runs above, say, 800 keV).

4. MAGNETIC FIELD CANCELLATION SYSTEM

Over the last several years, the residual magnetic field in the region of the vacuum tank has been measured several times. Although the individual values vary, the range of the residual fields is quite constant. The results of a recent survey are given in Table XI. As shown each residual component varies about 0.5 to 1.3 milligauss. This is quite small compared to the uncompensated earth's field components of ~ 550 (vertical) and ~ 220 (north-south) milligauss. It should be noted that most of these measurements are made inside the vacuum tank with a hand-held probe. The accuracy is, therefore, limited by the uncertainty in the probe orientation.

The effect of the residual field on the energy calibration constant is approximately proportional to the average of the vertical component. From the data in Table XI, the average of the values measured on the optic circle is about 0.06 milligauss. Compared to the field of 22 gauss needed to focus 50-keV electrons (and higher values at higher energies), this average residual field is completely negligible. Although the survey in Table XI was made immediately after the currents in the cancellation coils had been adjusted, the above mean vertical residual is typical. Another measurement, made about one year after the coil currents were adjusted, gave an average vertical residual of 0.01 milligauss.

As noted earlier, this compensation system does not have any automatic tracking capability. Therefore, short-term field variations will not be compensated.

TABLE XI

Residual Magnetic Field

Values are within approximate volume of orbits for resolution of 1%.

<u>Position</u>		<u>Residual Field (100 units = 1 milligauss)</u>		
<u>Azimuthal</u>	<u>Radial & axial</u>	<u>vertical</u>	<u>north-south</u>	<u>east-west</u>
source	optic circle	18	1	-46
source valve	r & Z maximum ^a	17	13	-36
	r & Z minimum ^a	12	1	-37
baffle plane	optic circle	3	- 4	-15
	r & Z maximum	10	- 5	-13
	r & Z minimum	- 8	-14	-32
center	optic circle	- 4	- 2	22
	r & Z maximum	25	-25	39
	r & Z minimum	-36	6	-45
secondary baffle plane	optic circle	-27	28	37
	r & Z maximum	-30	7	55
	r & Z minimum	-30	49	13
detector valve	r & Z maximum	-37	34	-71
	r & Z minimum	-14	57	-61
detector	optic circle	-11	29	-83
Range - on optic circle		45	49	120
- total		62	82	138

^a These positions correspond to the approximate extremes of the orbits for a resolution of 1%; the large possible baffle opening.

5. FIELD SHAPE

Some measurements of the radial variation of the magnetic field from the spectrometer were made. The values agreed with the calculated shape and showed the expected deviation from the ideal field near the outside radius of the tank. (These data were not of sufficient quality and quantity to merit a detailed presentation.)

6. LUMINOSITY AND RESOLUTION

A short series of measurements was made of the luminosity vs resolution. For these sources, the gamma-ray emission rates were measured with calibrated Ge(Li) spectrometers. From the previously measured, or theoretical, conversion coefficients, the electron emission rate was determined for the line of interest. From a comparison of this value with the measured peak counting rate, the transmission was determined. (This transmission includes the detector slit acceptance factor.) The experimental resolution R , transmission T , and luminosity L were determined for a number of baffle and detector slit settings. Table XII gives some of the resulting values.

The measured L values are shown in Figure 21 along with those of several other spectrometers. Generally, the best system is the one with largest L value at a given resolution. In Figure 21, the higher luminosity of the Chalk River instrument is due primarily to its larger size and resulting larger source size. For our instrument and most of the others, the luminosities are less than the optimum values. This results from the fact that the sources are generally not as long as the spectrometer optics would allow.

TABLE XII

Performance Characteristics

Measured transmission, luminosity and resolution for three particular sources.

Sample	Line	Source (cm)		I	L (cm ²)	R (%)
		height	width			
¹⁹² Ir	316L ₂	1	0.0037	7.2×10^{-5}	3×10^{-7}	0.008
	316 ₂	1	0.015	3.9×10^{-4}	6×10^{-6}	0.018
¹⁸² Ta	264K	2	0.075	7×10^{-4}	1×10^{-4}	0.08

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Fig. 21 Plot of measured luminosity-resolution values for several $\pi\sqrt{2}$ electron spectrometers. The Colorado system has an iron return flux path; the remainder are iron-free spectrometers. Our instrument is labeled NRTS.

7. SI DETECTOR EFFICIENCY

For an iron-free spectrometer such as this one, it is assumed that the transmission is independent of the magnetic field (i.e., electron energy). Therefore, the observed spectrum (i.e., count rate as a function of the spectrometer current) can be converted to the spectrum emitted by the source by correction for those pulses which are below the discriminator level.

The observed distribution of pulse amplitudes is shown in Figure 22 for electrons of 89 and 253 keV. The detection efficiency can then be determined by comparing the number of counts in this spectrum (after subtraction of the background, including the noise) with that obtained in a similar spectrum in coincidence with the discriminator output. However, one correction must be made. The singles (i.e., noncoincidence) spectrum must be extended under the noise to zero energy as illustrated in Figure 22. The shape of this extrapolated curve was determined from these experimental data and the theoretical calculations and experimental data in Reference 14.

It is not necessary to measure the coincidence spectrum at each electron energy. The coincidence count/singles count should be a function of the channel, but not of incident electron energy. The ratio was determined from the average of several measurements at different energies and is shown over the range that it varies in Figure 23.

In normal operation, the amplifier has a gain setting of 1000 and the discriminator setting is 250 (i.e., nominal 2.5 volts). However, in this situation many of the amplified pulses are saturated and might

Fig. 22 The observed pulse-height spectra for 89- and 253-keV electron lines from ^{182}Ta counted with the silicon surface-barrier detector. The spectra have been extrapolated under the noise to zero energy as shown by the solid lines.

not be analyzed satisfactorily by the multichannel analyzer (and, in fact, might be completely rejected). Therefore, in addition to these settings, a set of measurements was made with the gain and discriminator settings both reduced by a factor of 5 (to 200 and 50, respectively). It is assumed that the efficiency measured at the reduced gain is applicable to the operating conditions.

Fig. 23 Measured cutoff function for the discriminator and the pulse-height spectra as shown in Figure 22.

The results of these measurements are shown in Figure 24. Above 150 keV, the curves for the two amplifier gains are in excellent agreement (viz., difference are $\approx 0.25\%$). At low energies, there is some difference ($\approx 22\%$) and the standard gain (i.e., 1000) data are preferred. These data were all obtained with the detector at room temperature. For low-energy measurements, the detector would normally be cooled with a dry ice and alcohol mixture. The resulting reduction in the noise level allows a lower discriminator setting and a higher efficiency, especially at low energy (i.e., < 100 keV).

Fig. 24 Measured detection efficiency for silicon surface-barrier detector operated at room temperature. The data are for measurements at two amplifier gains (200 and 1000).

It was noted during these measurements that the shape of the discriminator cutoff (Figure 23) varied with the timing of the coincidence gating signal and the analog signal. Some coincidence spectra were obtained for the maximum delay time range that gave reasonable coincidence spectra. This resulted in a shift of the curve in Figure 23 by about one channel and a change in the shape. For electrons of 125 keV, the resulting change in the measured efficiency was determined to be $\sim 0.2\%$. Since all of the efficiencies would change in the same direction and we are generally interested only in the relative efficiency, this effect is negligibly small.

TABLE XIII

Variation in Detection Efficiency with Discriminator Setting

<u>Amplifier Gain</u>	<u>Discriminator Setting</u>	<u>Detection Efficiency</u>	<u>Change in Efficiency</u>
1000	230	0.908	+ 1.2%
	250	0.897	---
200	40	0.918	+ 3.3%
	50	0.889	---
	60	0.866	- 2.6%

The change in efficiency as a function of the discriminator setting was also measured for 125-keV electrons and is given in Table XIII. These results indicate that there should be no problem in reproducibility of the efficiency when the discriminator level is reset to these values.

8. EXPERIMENTAL DATA

Measurements have been made of the continuous electron (or positron) spectra of ^{32}P , ^{84}Rb , ^{86}Rb and ^{124}Sb . These data were taken with a resolution of 0.3% with sources made either by drying a solution or by vacuum evaporation. The different resulting source thicknesses should give information on the electron scattering the source. Spectra were taken with different source holder configurations to determine the scattering from the source backing and other nearby material.

There are several experimental problems involved in measurements of continuous spectra which are not as important when discrete spectra are studied. The shape of the continuous spectrum can be distorted by

counting (1) electrons scattered from the walls of the vacuum chamber, (2) electrons produced by gamma rays striking the chamber walls, and (3) electrons which are scattered (and change energy) in the source. Initial studies of the first two effects have been made. As noted earlier the primary baffles which define the transmission and resolution of the spectrometer are 78° from the source. It is therefore possible for electrons or gamma rays to pass through this baffle opening and strike and vacuum chamber walls. For some of the resulting energies and emission angles the scattered secondary electrons can then be counted. The magnitude of these effects has been studied crudely by the introduction of a secondary baffle placed 78° from the detector. This baffle should intercept many of the scattered and secondary electrons.

For the continuous electron spectrum from the decay of ^{32}P (end point 1710 keV), spectra taken with and without the secondary baffle are shown in Figure 25. The two spectra are compared by subtracting the background, normalizing and subtracting the two spectra. This difference divided by the associated errors is also shown. If there is no difference between the two spectra except for the statistical fluctuations, the sum of the squares of these residuals should be ~ 1.0 . For two such comparisons the actual values are 1.08 and 1.39. In the second case, the deviation from 1.0 may result, in part, from variations in the background during the experiment. This lack of any definitive change in these spectra indicates that the scattered electrons do not contribute significantly (compared to the counting statistics) in this case.

Fig. 25 Continuous electron spectrum of ^{32}P measured with and without a secondary baffle. The differences between the two spectra (after background subtraction and normalization) are shown at the bottom in units of the associated standard deviations. These spectra were taken with the primary baffle set at a resolution of 0.15% and the secondary baffle set at 1.0%. The data spans the energy range 120 to 1730 keV.

The effect from electrons produced by gamma rays striking the chamber walls was studied under a variety of experimental conditions with a 1-mci source of ^{65}Zn . This source does not emit a continuous electron spectrum; its radiations consist of a 1115-keV gamma ray and the associated conversion-electron lines, together with x-rays and positrons from the "beta" decay process. The electron spectrum was scanned from 120 to 740 keV with the primary baffle set at a resolution of 0.15% and the secondary baffle at 1.0%. The total count (for 840 minutes) in each spectrum is given in Table XIV. These results show a factor of ~ 3 reduction in the electron count rate, which indicates the desirability of using the secondary baffle in some experiments.

Internal-conversion-electron spectra have been measured for ^{160}Tb , ^{192}Ir , ^{182}Ta , $^{184\text{m}}\text{Re}$, ^{183}Re and ^{183}Ta . Figure 26 shows the K, L, M and N lines for the 316-keV transition from ^{192}Ir . These spectra were measured at a resolution of 0.017%. This resolution agrees with the value of 0.016% estimated for the source width (and baffle and detector slit settings). As shown in the figure, the natural width of the

TABLE XIV
Counts in ^{65}Zn Electron Spectrum
With and Without Secondary Baffle

Secondary baffle corresponds to 1% resolution; 840 minute count time.

<u>Configuration</u>	<u>Counts</u>		
	<u>Gross</u>	<u>Background</u>	<u>Net</u>
No secondary baffle	22,811 $\pm$ 144	20,832 $\pm$ 151	1,979 $\pm$ 209
Secondary baffle	21,546 $\pm$ 147	20,918 $\pm$ 145	630 $\pm$ 206

Fig. 26 Internal-conversion lines for K, L, M and N shells for 316-keV gamma ray from decay of ^{192}Ir . The lines have a resolution of 0.017%, except for the K which is wider due to the natural width of the atomic K shell.

K atomic level in platinum is sufficient to broaden the K line to a resolution of 0.024%. A careful analysis of the L lines also indicates a probable difference in the width of these lines. This illustrates the possibility of doing some atomic physics measurements with this instrument.

The ability to resolve closely spaced gamma-ray transitions is illustrated by the data from the decay of ^{183}Ta shown in Figure 27. With an energy separation of only 0.3 keV at 313 keV, these transitions would not be resolved with a Ge(Li) gamma-ray detector, except by gamma-gamma coincidence techniques.

Fig. 27 Spectrum of electrons from decay of ^{183}Ta showing K and L lines of two gamma rays of 313 keV.

Fig. 28 Measured 264 K and 1121 K conversion lines from the decay of ^{182}Ta . The difference in resolution is due to electron scattering in the source.

Figure 28 shows the 264 K and 1121K lines from the ^{182}Ta . Here the large difference in resolution is due to electron scattering in the source. This source was made for the study of the high-energy lines (i.e., above 800 keV).

Internal-conversion electron data from the decay of ^{184}Re and $^{184\text{m}}\text{Re}$ have been published,^[15] those from the decay of ^{183}Re have appeared in a thesis^[16] and some of those from the decay of ^{182}Ta are being prepared for publication.

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