1957

Reconstruction of thin lens Beta ray spectrometer.

Armstead, Robert C.
Monterey, California : Naval Postgraduate School

https://hdl.handle.net/10945/14549
RECONSTRUCTION OF THIN LENS
BETA RAYSPECTROMETER

Robert C. Armstead
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THIN LENS BETA RAY SPECTROMETER

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RECONSTRUCTION OF

THIN LENS BETA RAY SPECTROMETER

by

Robert C. Armstead

Lieutenant Colonel, United States Marine Corps

Submitted in partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE

IN

PHYSICS

United States Naval Postgraduate School
Monterey, California

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THIN LENS BETA RAY SPECTROMETER

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This work is accepted as fulfilling
the thesis requirements for the degree of
BACHELOR OF SCIENCE
IN
PHYSICS

from the

United States Naval Postgraduate School
ABSTRACT

The project described in this paper was undertaken during the 1956-57 academic year at the U. S. Naval Postgraduate School, Monterey, California.

The purpose of this project was to redesign and make operational a thin magnetic lens Beta-ray spectrometer which could be used to determine the beta particle spectrum emitted by radioisotopes. Discussion and data concerning the theory, operation, construction, calibration and uses of this spectrometer is assembled herein. It is hoped future researchers will find useful this information and equipment when adequate radioactive sources are made available through use of the AGN-201 nuclear reactor soon to be in operation in the U.S.N.P.S. Engineering School.

The equipment consists of the spectrometer with accessory detectors and vacuum system, two 220v.D.C. motor generator sets and electronic control systems to regulate current to the spectrometer magnet coils.

The writer wishes to express his appreciation to Lieutenants W. H. Broadfield and R. Sharp, U. S. Navy, his colleagues on this project; to Dr. Edmund Milne, PhD, for his advice and guidance; to Mr. M. K. Andrews, Chief Opticalman R. C. Moeller, U. S. Navy, and Mr. K. Smith for their willing cooperation and skillful assistance when aiding in construction and assembly of this equipment.
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# TABLE OF SYMBOLS

1. \(-\ c\) Velocity of light  
2. \(-\ f\) Focal length  
3. \(-\ H\) Magnetic field strength  
4. \(-\ I\) Coil current  
5. \(-\ mv\) Electron momentum in \(H\) units  
6. \(-\ N\) Number of coil turns  
7. \(-\ T\) Kinetic energy  
8. \(-\ u\) Distance from source to center of coil  
9. \(-\ v\) Distance from detector to center of coil  
10. \(-\ v_e\) Electron velocity  
11. \(-\ \rho\) Radius of curvature
1. Introduction.

An electron spectrometer for the study of radiation from radioactive isotopes and particle accelerators was redesigned and assembled from equipment and drawings obtained from U. S. Naval Radiological Defense Laboratories. This spectrometer is of the thin magnetic lens type similar in principle to that built by Deutsch et al. /6/. Its principle of operation is closely analogous to that of an optical focal isolation spectrometer. Electrons of one particular energy, starting from the source are focused by the field of the lens coil on a geiger counter window. Electrons of other energies will strike the wall of the chamber or baffles provided for this purpose. The characteristics of the short lens magnetic spectrometer differ appreciably from those of the conventional 180 degree type. The short lens is primarily a high intensity rather than extreme resolution instrument. However, in most studies of radioactive radiations, the practical resolution is limited by factors other than ultimate possible resolving power of the spectrometer. Thus the thin lens spectrometer permits the attainment of better overall performance in the type of measurement required in the study or radioisotope spectra.

2. Theory of Thin Lens Spectrometer.

The principle on which the magnetic lens spectrometer is designed is the same as that used in focusing in the electron microscope. Hence the term magnetic lens is used. The thin lens type of apparatus assembled in this project consists of a cylindrical vacuum chamber around the mid-section of which is wound a coaxial coil of copper wire (Figs. 1 and 2). When a current is passed through the coil, a non-uniform magnetic field is produced in the cylinder with its direction at the mid-point parallel
a₁ - Inside radius of coil
a₂ - Outside radius of coil
d - Inside diameter of main tube
l - Distance from source to counter
u - Distance from source to center of coil
v - Distance from detector to center of coil = 50.00

C - Counter
D - Coil
S - Source
T - Main Tube

t - Thickness of coil

<table>
<thead>
<tr>
<th>ITEM</th>
<th>USNPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>100.00*</td>
</tr>
<tr>
<td>u</td>
<td>50.00</td>
</tr>
<tr>
<td>v</td>
<td>50.00</td>
</tr>
<tr>
<td>t</td>
<td>15.88</td>
</tr>
<tr>
<td>a₁</td>
<td>10.17</td>
</tr>
<tr>
<td>a₂</td>
<td>27.30</td>
</tr>
<tr>
<td>d</td>
<td>17.78</td>
</tr>
</tbody>
</table>

*All dimensions in centimeters

Fig. 1

SPECTROMETER DIMENSIONS
Fig. 2
to the axis of the cylinder, but of varying intensity along the axis.
The radioactive source is placed at one end of the cylinder and a thin walled Geiger-Mueller tube detector at the other end. The particles leaving the source move toward the detector in a spiral path under the focusing influence of the magnetic field and the restrictions imposed by the baffle system. For a given value of the magnetic field only those particles of a particular velocity or energy will reach the detector.
This energy value can be calculated by knowing the value of the magnetic field and the dimensions of the spectrometer. The current \( i \) through the \( n \) turns of the coil and the momentum of the focused electrons are related by the formula
\[
f = C\left(\frac{\rho}{ni}\right)^2
\]
where \( \rho = (e/c)mv \) is the "momentum" in units of \( \hbar \), where \( \rho \) is the radius of the circular orbit these particles would have in a uniform magnetic field, \( H \). \( C \) is a constant which depends upon the shape and size of the coil. \( F \) is the focal length and is related to the source distance \( u \) and detector window distance \( v \) (Fig. 1) by the thin lens formula
\[
\frac{1}{f} = \frac{1}{u} + \frac{1}{v}
\]

The above discussion is adequate for a general understanding of the principles upon which the spectrometer of this project is based. For a detailed treatment of the calculations and principles, the reader is referred to a review by Deutsch. /6/.

In actual practice the analytical calculations involved in the design and operation of the thin lens spectrometer are complex and several simplifying approximations must be used. Therefore empirical methods are used to calibrate and operate the instrument. A brief discussion of these experimental techniques appear under calibration.
3. Mechanical Components.

a. Spectrometer Assembly.

The spectrometer assembly is shown in Figs. 1, 2, 3, and 4. It consists of the following units which are mounted on a castored table so that the spectrometer tube may be aligned with the earth's magnetic field.

(1) Water cooled lens coil

The magnetic coil consists of a set of five concentric brass spools wound with No. 14 copper wire. To provide adequate cooling, 1/4 inch O.D. copper tubing was incorporated as the outer layer of each spool. Coil data and winding connections are shown in Table 1 and Fig. 5. The individual cooling coils are connected to a common manifold thence to a cold water supply. The cooling water to any individual spool may be regulated by adjustment at the manifold. By use of water cooling, the current carrying capacity of the magnet coils has been materially increased.

(2) Spectrometer chamber

The chamber consists of an aluminum tube 9 inches in inside diameter, 1/4 inch wall thickness, and 50 inches long. It is made vacuum tight at each end by the use of end plates provided with O-rings for seals. The detector assembly, consisting of an end window Geiger-Mueller tube in a brass holder, and source tube of solid brass rod with source holder, are inserted at opposite ends through these end plates. The linear position of both source and detector is adjusted by externally mounted brass collars. Connected
Fig. 3
SPECTROMETER ASSEMBLY DETECTOR END
Fig. 4
**TABLE I**

**DATA FOR NEW COIL**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>SPOOL A</th>
<th>SPOOL B</th>
<th>SPOOL C</th>
<th>SPOOL D</th>
<th>SPOOL E</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Number of layers of winding</td>
<td>22</td>
<td>18</td>
<td>16</td>
<td>12</td>
<td>14</td>
<td>82</td>
</tr>
<tr>
<td>2. Average number of turns per layer*</td>
<td>97</td>
<td>95</td>
<td>97</td>
<td>99</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>3. Total number of turns on spool (item 1 x item 2)</td>
<td>2134</td>
<td>1710</td>
<td>1552</td>
<td>1188</td>
<td>1372</td>
<td>7956</td>
</tr>
<tr>
<td>4. Measured resistance (ohms)</td>
<td>15.5</td>
<td>17.5</td>
<td>19.5</td>
<td>17.5</td>
<td>24.0</td>
<td>94.0</td>
</tr>
<tr>
<td>5. Length of wire (ft) (item 4 x 1000/2.58)**</td>
<td>6010</td>
<td>6790</td>
<td>7560</td>
<td>6790</td>
<td>9300</td>
<td>36,450</td>
</tr>
<tr>
<td>7. Inside diameter of winding (inches)</td>
<td>8.000</td>
<td>11.400</td>
<td>14.550</td>
<td>17.500</td>
<td>20.000</td>
<td>8.000</td>
</tr>
</tbody>
</table>

*Based on actual count of several random layers.

**Based on nominal resistance for #14 wire of 2.58 ohms/1000 ft at 25° C.

Note: Nominal weight of #14 wire is 12.4 lb/1000 ft.
to the source end-plate is a vacuum tight gate valve allowing for withdrawal and insertion of source holder without loss of vacuum. Located internally are lucite annular rings which serve as focusing slits and absorbers of non-focused particles. Equi-distant from the source and detector on the central axis of the tube is a lead pig which in conjunction with the lucite rings forms the focusing slit. At the detector end an externally adjustable aluminum baffle provides a means by which the resolution can be varied. A ventral pipe at the source end of the tube provides an outlet to the vacuum system.

b. Vacuum System.

This system is made up of three major components

(1) Oil diffusion pump
(2) Fore pump
(3) The cold trap

With this system using liquid nitrogen in the cold trap a pressure of about $1 \times 10^{-6}$ mm hg is attainable. For most purposes a pressure of $10^{-2}$ mm of hg, attainable with the fore pump alone, is quite adequate. /10/.

c. Cooling tank.

This is a galvanized sheet metal tank containing 12 gallons of transformer oil. It is used to cool a one ohm 500 watt precision resistor used in the magnet coil current control circuit. The oil is in turn cooled by use of a standard refrigeration condenser coil through which is circulated discharge water from the magnet and diffusion pump cooling coils. The wooden tank cover is used as a mounting board for various electrical terminal connections (Fig. 3).
4. Electrical Components

The spectrometer electronic and control circuits are shown in Fig. 7. They can be divided into the following; Lens coil current system, Earth's magnetic field canceling system, Detector system, Vacuum measuring system, and A.C. power supply system. Figs. 6 through 14 show all electrical components.

a. Lens coil current.

The block diagram of the lens coil current system is shown in Fig. 8. The coil current supply consists of two 220 volt D.C. 8.7 amperes 2.0 kw. motor generator sets connected in series. The current output of these generators is controlled through the motor generator fields. The current for these fields is the plate output of a power amplifier consisting of 32 tubes (807's) connected in parallel. Regulation of the generator output is attained by causing the output current to control the grids of the 807's as explained below.

To achieve regulation, a signal is picked off across a 150 mv shunt (mounted on cooling tank cover) in series with a one ohm 500 watt zero temperature coefficient resistor immersed in the cooling tank. This signal is fed to the voltage reference and control amplifier whose voltage output is connected to the grids of the 807's. An increase in coil current increases the signal on the voltage on the grids of the 807's which in turn decreases the coil current. The static output of the voltage reference and control amplifier can be varied by adjustment of helical potentiometer located on the front panel of this instrument.

By use of this potentiometer the coil current can be varied from approximately 1.5 to 14.5 amperes with the lens coils connected as shown in Fig. 6. These values may be changed by altering the total resistance
Fig. 8

Lens-Coil Current Circuit, Block Diagram

Motor-Generator Sets

Rubicon Potentiometer

Brown Recorder

Reference Voltage and Control Amplifier

1 ohm 500-watt

100 mv shunt

50 mv shunt

Series Fields

M-G Fields

Lens Coil

60 uf.
Fig. 14

COIL CURRENT CONTROL PANEL
of the lens coil which can be accomplished by varying the series-parallel arrangement of the individual coils. Zero coil current is not attainable due to residual magnetism in the field coils of the motor generator sets.

Also used in the regulation is a buckler whose output is connected to the power amplifier and motor generator fields. This buckler, as its name connotes, opposed changes in the power amplifier output thereby smoothing out fluctuation or transients.

The actual percentage current fluctuations were not obtained but should be made part of the alignment and calibration of the instrument. It was however noted, in the work done in making the instrument operable, that the coil current measured by an ammeter and rubicon potentiometer was very stable.

Coil current is measured through the use of a rubicon potentiometer connected across a 100 mv shunt in the lens coil circuit.

b. Earth's magnetic field canceling.

This is a variable D.C. voltage supply connected to two Helmholtz-coils located above and below the lens coil (Fig. 2). These coils compensate for the vertical component of the earth's magnetic field. Cancellation is accomplished by varying the current in the coils and balancing a dip needle to zero deflection. The effects of the horizontal component of the earth's magnetic field are canceled by aligning the axis of the spectrometer in the direction of this component.

c. Detector.

For detection of focused particles an end window Geiger-Mueller tube is used. The output of the detector is fed into a scaler and count rate meter. For permanent records and correlation with current fluctuations,
a recorder is attached to the count rate meter.

d. Vacuum measuring.

This consists of a VG-1A ion tube connected to the high vacuum side of the diffusion pump and is used for accurate evaluation of the system pressure. The pressure in mm of hg can be obtained by using any standard ion gauge which is adaptable to use with a VG-1A tube.

Inserted in the line between the forepump and diffusion pump is a pirani tube for rough measurements and determining safe pressure at which to start up the diffusion pump. This vacuum can be read by connecting the pirani tube to any gauge.

e. A.C. power supply.

One hundred seventeen volts alternating current is supplied from standard circuit breaker protected laboratory outlets to the electronic components through relays controlled by start-stop buttons on the control panel (Fig. 9). The A.C. block diagram is shown in Fig. 10.

5. Operating Procedure.

The operational procedure is in itself quite simple and easily mastered. It was deliberately so designed to make the spectrometer available for usage by a maximum number of researchers without time-consuming prior training.

The operating procedure may be divided into two major steps; Start up procedure and Coil current control.

a. Start up procedure.

All starting controls except the motor generator start, and reference voltage and control amplifier on-off, are located on main control panel (Fig.9). The on-off switch for the voltage reference and control amplifier is located on that chassis. However, it is generally left in the "on" position as A.C. power to this unit is controlled through the main power
relays $R_1$ and $R_2$ (Fig. 10).

The motor generators are started through individual starters located adjacent to the motor generator sets. These starters will not operate unless motor generator control relay on main control panel is closed. The motor generators can be stopped from the main control panel by opening the master relay or motor generator control relay, both of which are located on the main control panel.

All other A.C. controls are clearly marked and self-explanatory. Power cannot be applied to bucker until the one minute time delay relay in the power amplifier supply closes. This time delay relay allows sufficient time for warmup of the mercury vapor rectifier filaments before applying plate voltage from A.C. line or inadvertently through the bucker since the two units are interconnected.

b. Coil current control.

Lens coil current is controlled by two potentiometers for coarse and fine control located on the front panel of the voltage reference and control amplifier (Fig. 14).

Coil current is measured by the voltage drops across a 100 mv shunt as measured by a rubicon potentiometer.

Care must be taken in the operation of the spectrometer to assure that distances $u$ and $v$ (Fig. 1) accurately duplicate with those used in the calibration of the spectrometer.


a. Alignment of axes.

In order to insure that the axes of the various baffles coincide in direction and in position with the symmetry axis of the magnetic field, in short lens spectrometers the baffles, the source, and the counter are
rigidly fixed to the walls of the vacuum chamber. To get proper alignment, this entire rigid unit can be displaced slightly with respect to the coil by means of leveling screws (Fig. 2). This adjustment is very critical and can be made by trial and error, or by a method described by N. F. Verster /17/. The author achieved some success in alignment by the trial and error method. However, the source used was not of the proper size or type. It is recommended that an alignment check be made with the proper type source before calibration is attempted.

b. Adjustment of focal length.

Initially the counter window and source are each positioned approximately 50 centimeters from the lens coil center. By use of the locking collars their position is adjusted until optimum focusing results.

c. Calibration.

There are two basic methods by which the instrument may be calibrated; analytical and experimental. However, the analytical method is complex and is not considered practical since it has inherent inaccuracies which require experimental calibration for verification.

Experimentally, calibration can be accomplished through the use of an isotope producing a monoenergetic beta with a known $H_{\beta}$ value. Since the spectrometer lens coil contains no iron, the field, "$H\beta$", is proportional to the current, "$I\beta". Hence for a given source-detector arrangement we may write /10/

$$H_{\beta} = kI$$

where $k$ can be determined through the use of the isotope mentioned above.

As can be seen from the above formula, this is a linear relation so that determination of current by use of such an isotope gives a calibration curve for the instrument.
Proper selection of the isotope, i.e., thorium B, yields a value of k which is accurate over a wide range of energies. However, should a low-energy radiation study be undertaken, such that a different arrangement of coil windings is necessary, a new value of k must be determined.

In the U.S.N.P.G.S. spectrometer coil current is not measured directly but as a voltage drop across a 100 mv shunt by means of a rubicon potentiometer. This method of current determination is more accurate than the direct use of an ammeter. The calibration curve can be plotted as a function of voltage drop rather than current since E=IR. Therefore,

\[ H_p = \frac{kE}{R} \]

where E is voltage drop measured by the ribicon potentiometer and R is the resistance of the 100 mv shunt. Since R is a constant H_p is determined when E is determined.

Once the H_p versus voltage calibration curve has been determined for this instrument, it can be used for beta spectrum studies where the beta particle velocities \( v_e \) are determined by /11/.

\[ H_r = 1704.5 \frac{v_e}{c} \left( 1 - \frac{v_e^2}{c^2} \right) \]

and knowing these velocities the kinetic energy is determined by

\[ T = 0.511 \left[ \frac{1}{\left( 1 - \frac{v_e^2}{c^2} \right)^\frac{3}{2}} \right] - 1 \]

The energy can be determined from H_p by combinations of these two formulas or construction of a curve of H_p versus T. The necessary values of H_p and T for such a plot may be found on page 287 of reference /11/.

7. Conclusion.

No actual experimental results were obtained due to lack of time and
the proper calibration sources. The construction of the spectrometer is completed. It is in an operating condition. Only calibration with an appropriate source is needed to make this instrument a valuable research tool at the U. S. Naval Postgraduate School.
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