A THIN MAGNETIC LENS BETA-RAY SPECTROMETER

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by

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ABSTRACT

A thin magnetic lens beta-ray spectrometer has been constructed for use in the study of nuclear decay schemes. The alignment and calibration of the spectrometer using a cesium 137 source is described. The spectrometer is found to have an approximate resolution of 3.6% for the 623.8 kev K internal conversion electron of cesium 137 and a spectrometer constant of approximately 242 gauss-centimeters per ampere. The stability of the instrument is severely limited by the battery power supply for the magnetic lens.

ACKNOWLEDGEMENTS

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Thanks to C. Kingston and R. Heskins of the physics shop without whose skillful aid this spectrometer could never have been completed.

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CHAPTER I.

INTRODUCTION

1.1 Purpose of this Investigation

The purpose of the work done, as described in this thesis, was to construct and test the operation of a thin magnetic lens beta-ray spectrometer. The thin lens spectrometer that was constructed is not a new concept in spectrometer design. The chamber, baffle construction and power requirements are as described in a thesis by Bradley (1). However, important changes have been made in chamber suspension, particle detection techniques and source mounting.

The primary use of this spectrometer is expected to be as a coincidence spectrometer. As such, internal conversion coefficients can be determined and the establishment of energy level schemes for radioactive nuclei can be made. The spectrometer is also expected to be used as a delayed coincidence spectrometer in order to determine the lifetimes of excited states. However, it is first necessary to establish the quality of the instrument as an ordinary beta-ray spectrometer and that is the purpose of this thesis.

CHAPTER II.

THE THIN LENS BETA-RAY SPECTROMETER

2.1 Theory of the Spectrometer

Ever since the time that it was understood that the beta-rays emitted by a radioactive substance are a mixture of electrons of different kinetic energies it has been known that these electrons could be separated according to their charge and velocity by means of a magnetic field. This provides a method of sorting out and studying the various energies present in a given beam of beta-rays. Such a magnetic field is used in a family of different beta-ray spectrometers which are called helical or lens spectrometers. These spectrometers utilize the focusing property of an axially symmetric magnetic field for electrons coming from a source located on the axis.

The focusing action of magnetic fields produced by long and short current carrying coils has long been known and there is a close analogy between ordinary light and electron optics when dealing with these "magnetic lenses". Three types of t he magnetic lens spectrometers have been developed:

(1.) The solenoid spectrometer which uses a uniform magnetic field to focus the electrons. The chief advantages of the uniform magnetic field are the possibility of explicit

calculation of the electron trajectories and less sensitivity to external magnetic fields.

(2.) The long lens or double lens spectrometer which uses a non-uniform axially symmetric magnetic field. This magnetic field is produced by two or more coils aligned along the axis of the spectrometer. The chief advantage of this spectrometer is its transmission. It has a greater transmission at the same resolving power than any other type of lens spectrometer.

(3.) The thin lens or short lens spectrometer which uses a non-uniform axially symmetric magnetic field confined to a small region between the source and detector. The chief advantages of the thin lens spectrometer are its flexibility in performance, ease of construction and simplicity of design.

The thin magnetic lens spectrometer was chosen to be constructed because of its simplicity and flexibility of use. This type of spectrometer was first built by Klemperer (2) and later by several others, including Deutsch, Elliot and Evans (3) and Jensen, Laslett and Pratt (4). Early theoretical calculations made by Deutsch were based on the principle of axial focusing, that is, particles leaving a point source on the spectrometer axis were considered to be focused on an image point also on the axis. Further study of the theory of focusing in thin

lens spectrometers brought about the more realistic principle of ring focusing. If the focusing action of a thin magnetic lens is examined, it is found that electrons with a larger initial slope to the axis cross the axis closer to the lens than electrons with the same momentum and a smaller slope. Therefore, the trajectories of the two electrons with the same momentum and slightly different initial slope will intersect. The family of electron trajectories will form an envelope which in space is an axially symmetric surface. Any point on the envelope constitutes "ring focus" for some small range of initial slopes. A theoretical study of ring focusing in a thin lens spectrometer has been done by Keller (5).

2.2 Equations for the Beta-ray Trajectories

To understand the action of the pure field on an electron which enters it with a definite constant velocity, v, from a region outside the field, it is important to remember that, in the most general case, both the field and the electron velocity have three components. This means that in each of the coordinate directions there will be two components of force acting on the electron which determine its motion in that direction. For example, in the axial direction, the tangential field component and the radial velocity component will determine one of these force

components; the other is determined by the tangential velocity component and the radial field component. Using cylindrical coordinates, the force components acting on the electron are as follows:

$$F_z = -\frac{e}{c} v_r H_\theta + \frac{e}{c} v_\theta H_r$$

$$F_r = -\frac{e}{c} v_\theta H_z + \frac{e}{c} v_z H_\theta$$

$$F_\theta = -\frac{e}{c} v_z H_r + \frac{e}{c} v_r H_z$$

If one makes use of the fact that an axially symmetric magnetic field $H(r,z)$ can be represented by the curl of a vector potential A_θ, whose direction is always azimuthal, and calculate the components of H in terms of A_θ, it is found by using cylindrical coordinates that:

$$H_r = -\frac{\partial}{\partial z} A_\theta$$

$$H_z = \frac{1}{r} \frac{\partial}{\partial r} (r A_\theta)$$

One also finds that $A_\theta = Hr/2$. H_θ is equal to zero in our case since the fields of focusing coils are rotationally symmetrical. By making appropriate substitutions the equations of motion of the electron can now be stated as:

$$\frac{d}{dt}(m\dot{r}) = mr\dot{\theta}^2 + \frac{e}{c}\dot{\theta}\frac{\partial}{\partial r}(rA_\theta) \qquad (1)$$

$$\frac{d}{dt}(m\dot{z}) = \frac{e}{c}r\dot{\theta}\frac{\partial A_\theta}{\partial z} \qquad (2)$$

$$\frac{d}{dt}\left(mr^2\dot{\theta} + \frac{e}{c}rA_\theta\right) = 0 \equiv \frac{dp}{dt} \qquad (3)$$

where $\dot{\theta}$ represents angular velocity.

Numerical intergration of the electron paths has been performed by Keller (5) for the case of a point source. He has also approximated the trajectories for a finite source. The electron trajectories in an axially symmetric non-uniform magnetic field cannot be calculated explicitly as in the case of the uniform field. Therefore, the above equations of motion for an electron in a cylindrically symmetric magnetic field with no azimuthal component will be reduced to a single equation and considered satisfactory for the electron trajectory.

In the above equations of motion for an electron,

r, z and θ are the cylindrical coordinates describing the position of a particle of charge e and relativistic mass m at time t. c is the speed of light. The particle speed, v, and hence also the mass, is a constant of the motion, since a steady magnetic field can do no work on a charge. The canonical angular momentum p about the symmetry axis is also a constant of the motion. By introducing it into the first two equations, the angular velocity $\dot{\theta}$ can be eliminated with the result:

$$\frac{d}{dt}(m\dot{r}) = \frac{e^2}{mc^2}\left(\frac{pc}{er} - A_\theta\right)\left(\frac{pc}{er^2} + \frac{\partial A_\theta}{\partial r}\right) \qquad (4)$$

$$\frac{d}{dt}(m\dot{z}) = \frac{e^2}{mc^2}\left(\frac{pc}{er} - A_\theta\right)\frac{\partial A_\theta}{\partial z} \qquad (5)$$

The equations for an orbit are obtained from the equations of motion by replacing time by the coordinate z as the independent variable. The left-hand members of equations 4 and 5 can now be expressed as:

$$m\dot{z}^2\frac{d^2r}{dz^2} + m\frac{dr}{dz}\cdot\dot{z}\cdot\frac{d(\dot{z})}{dz}$$

and

$$m\dot{z}\ \frac{d(\dot{z})}{dz}$$

respectively.

In turn, $\dot{z}$ can be expressed in terms of the particle speed v by the relation:

$$v^2 = \dot{r}^2 + \dot{z}^2 + r^2\dot{\theta}^2$$

$$= \left[1 + \left(\frac{dr}{dz}\right)^2\right]\dot{z}^2 + \frac{e^2}{m^2c^2}\left(\frac{pc}{er} - A_\theta\right)^2$$

Carrying out the indicated substitutions, one obtains the single differential equation:

$$r''\frac{\left(\frac{mvc}{e}\right)^2 - \left(A_\theta - \frac{pc}{er}\right)^2}{1 + r'^2} - r'\left(A_\theta - \frac{pc}{er}\right)\frac{\partial A_\theta}{\partial z}$$

$$+ \left(A_\theta - \frac{pc}{er}\right)\left(\frac{pc}{er^2} + \frac{\partial A_\theta}{\partial r}\right) = 0$$

Primes indicate differentiation with respect to z. If one writes k for mvc/e (momentum of the particle in Hρ units*)

*See section 4.2

and sets $p = 0$, the equation reduces to:

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

This expression is the non-linear differential equation which was numerically integrated by Keller (5) using IBM machines.

CHAPTER III.

CONSTRUCTION OF THE SPECTROMETER

3.1 Materials

The momentum of the particles focused will be linearly related to the field strength. In order that the field intensity be proportional to the focusing current in the coils it is necessary to avoid the use of ferromagnetic materials in the construction. Therefore, for the most part the spectrometer was constructed of brass, copper, lead and aluminum. A few steel parts such as screws and bolts were considered acceptable if they were placed in regions of very low field.

3.2 Chamber

The vacuum chamber of the spectrometer was made from a brass tube of 45 inches length and 1/8 inch wall thickness. The inside diameter of the tube is 7 inches. Flanges to attach the end plates were soldered onto the ends of the tube. The flanges were designed to allow entry of the baffle system into the chamber and also to allow entry of the chamber into the coil. A two inch manifold enters the side of the chamber for evacuation.

Figure 3.1 shows the baffle placement in the spectrometer. Four baffles are made from 1/4 inch aluminum stock

and one is made from molded lead. The baffles are placed in such a way so as to limit the flux of particles and radiation down the tube.

At the geometrical center of the cylindrical chamber is suspended a lead plug of three inches in length and of sufficient diameter to shield the detector from the gamma radiation of the source.

In the midplane of the chamber is placed a baffle ring of 6 1/2 inches inside diameter. The function of this baffle is to reduce the number of particles which, by small angle scattering from the wall of the chamber, would be deflected into the counter.

A fixed ring with two inches inside diameter is located inside the chamber at a position about three inches from the source. The function of this baffle is to trap the many particles whose initial direction does not place them in the cone of particles to be focused. It prevents these particles from entering the detector by multiple scattering along the walls.

Two movable baffles are suspended by 1/4 inch brass rods which enter the chamber through seals in the detector end plate. These seals employ "O" rings to make a vacuum tight seal. If the rings are kept greased with a high vacuum grease, the rods may be moved without letting down the vacuum. The intention was to place these baffles

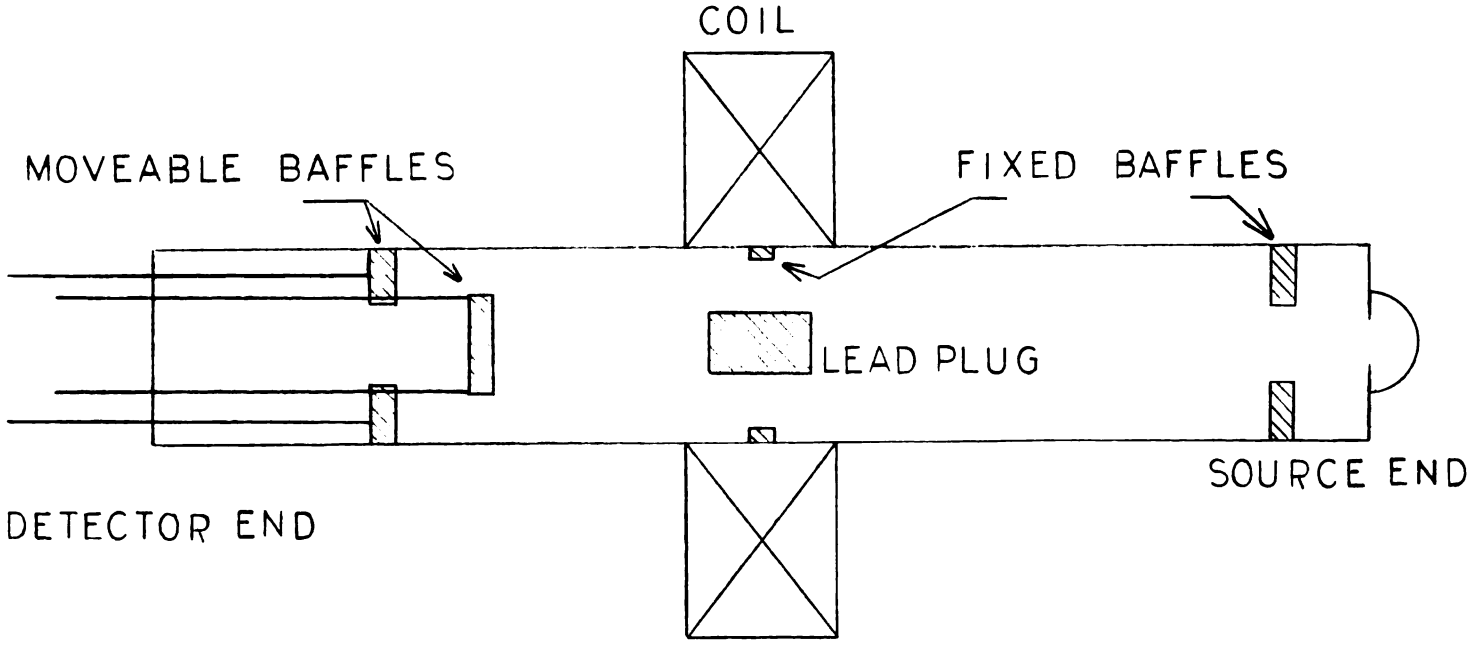

FIG. 3.1 BAFFLE PLACEMENT IN THE SPECTROMETER

near the point of ring focus and let them define the flux of particles entering the detector and thereby determine the resolving power of the spectrometer.

3.3 Coil

The magnetic field is produced by a coil consisting of five pies*. Each pie was made from 150 turns of 1/2 x 0.032 inch copper strip. 5 mil thick paper strip was wound between turns for insulation. Each pie was varnished and baked so it could be handled without danger of breakage. The five pies in series have a resistance of 1.5 ohms.

The coil spool was made from 1/8 inch rolled brass. The pies were placed on the spool and between each pie was placed a 1/8 inch brass disk for cooling. These disks are separated from the pies by fish paper. Around each disk was soldered small copper tubing through which cooling water can be passed. Two large aluminum end plates hold the coil assembly firmly together. These end plates also serve as the complete support for the spectrometer.

Leads from the pies are brought out to a terminal board which is mounted between the edges of the end plates. On this terminal board any desired connection can be made.

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*Wound by Barker Fowler Electric Co., Lansing, Michigan.

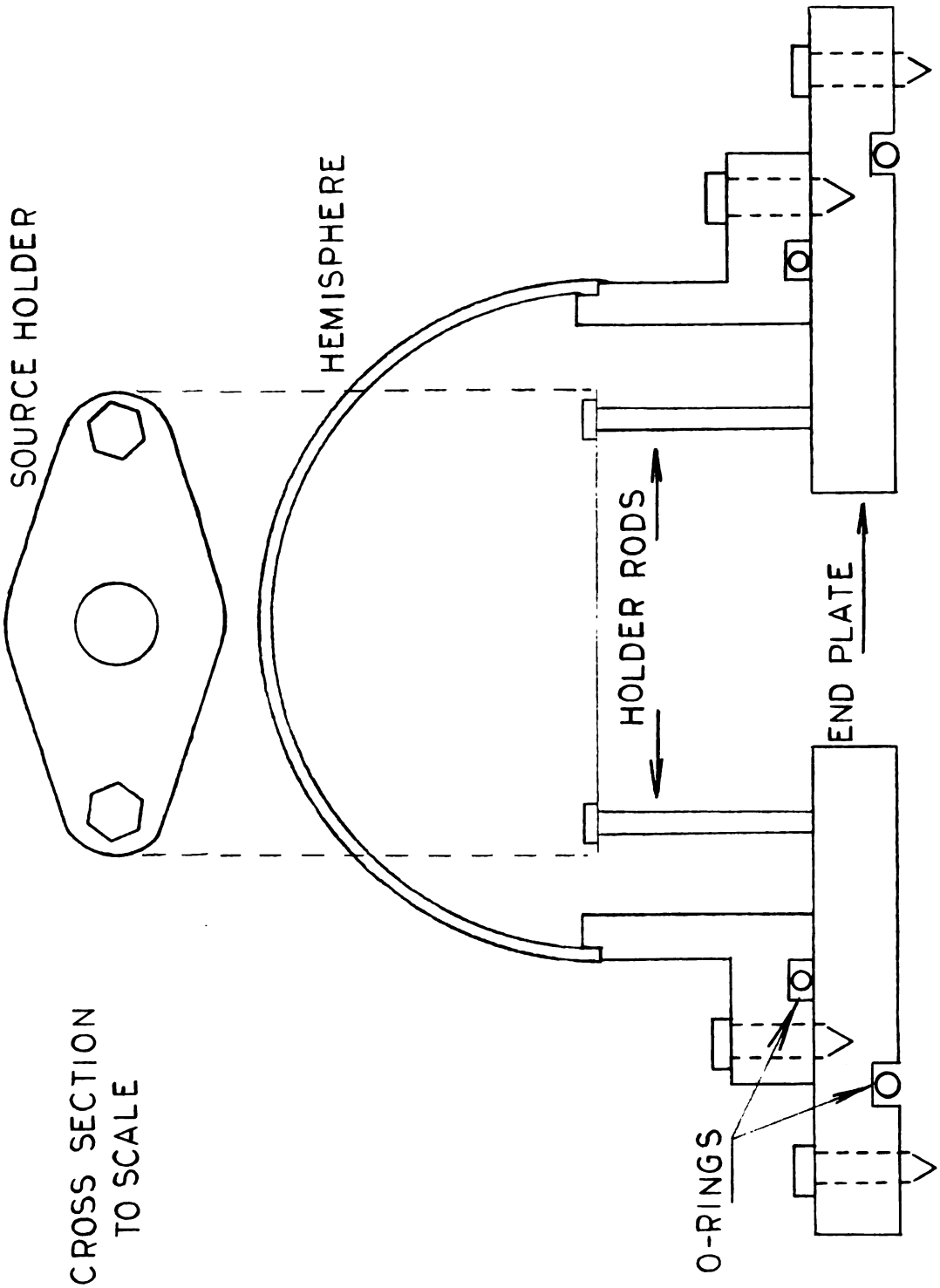

FIG.3.2 SOURCE END ASSEMBLY

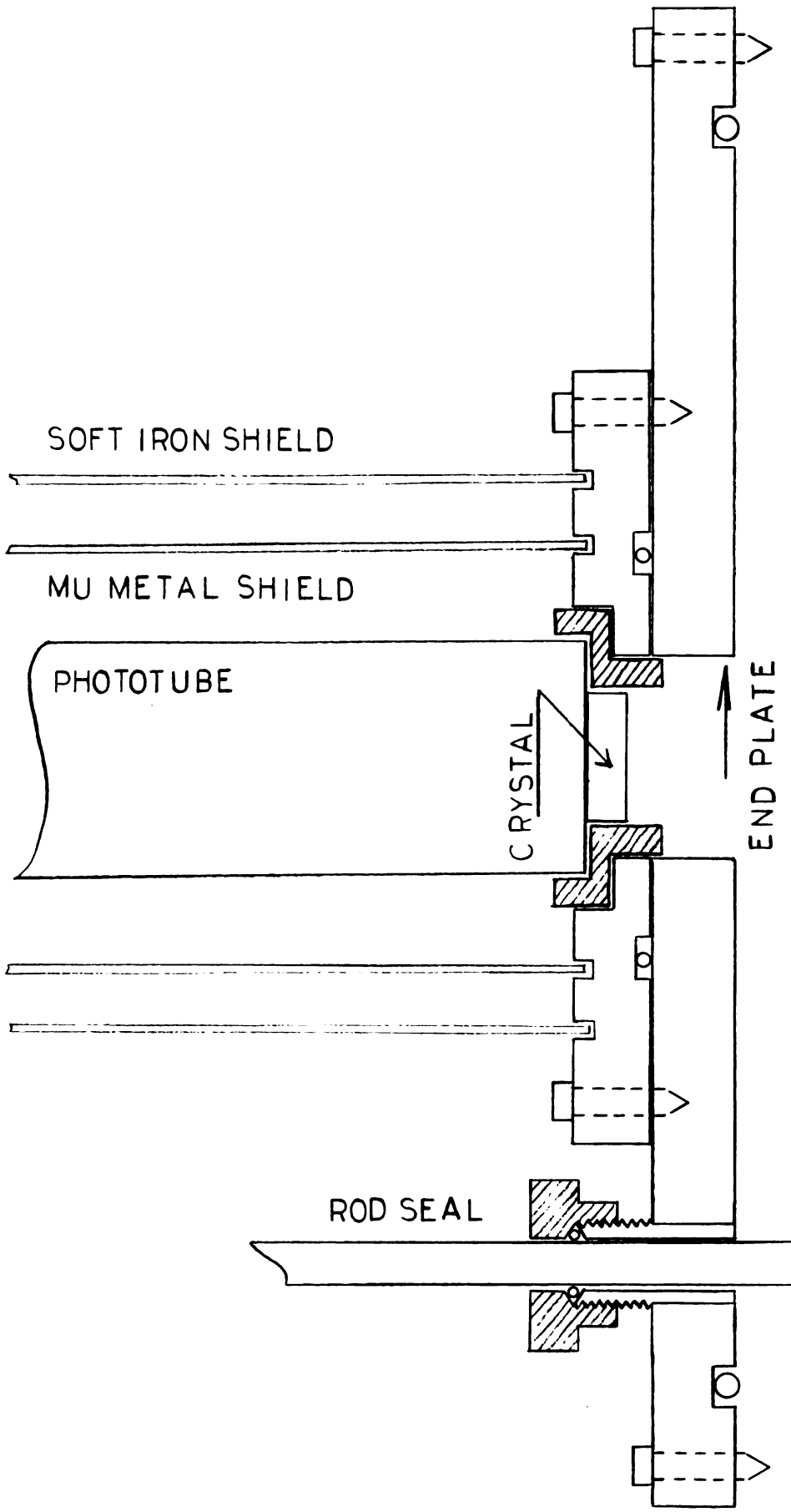

FIG. 3.3 DETECTOR END ASSEMBLY

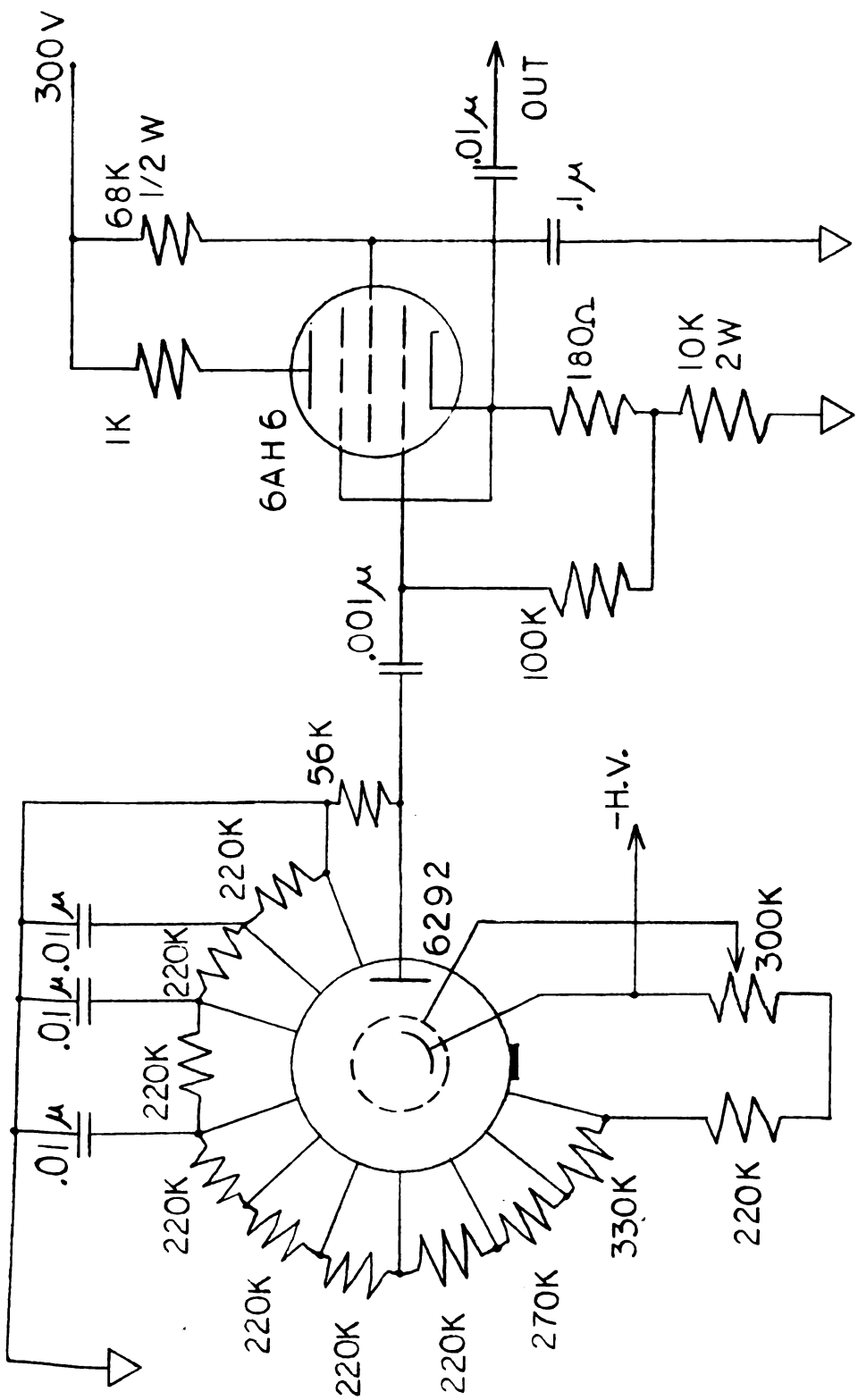

FIG.3.4 CATHODE FOLLOWER AND PHOTOTUBE CIRCUIT

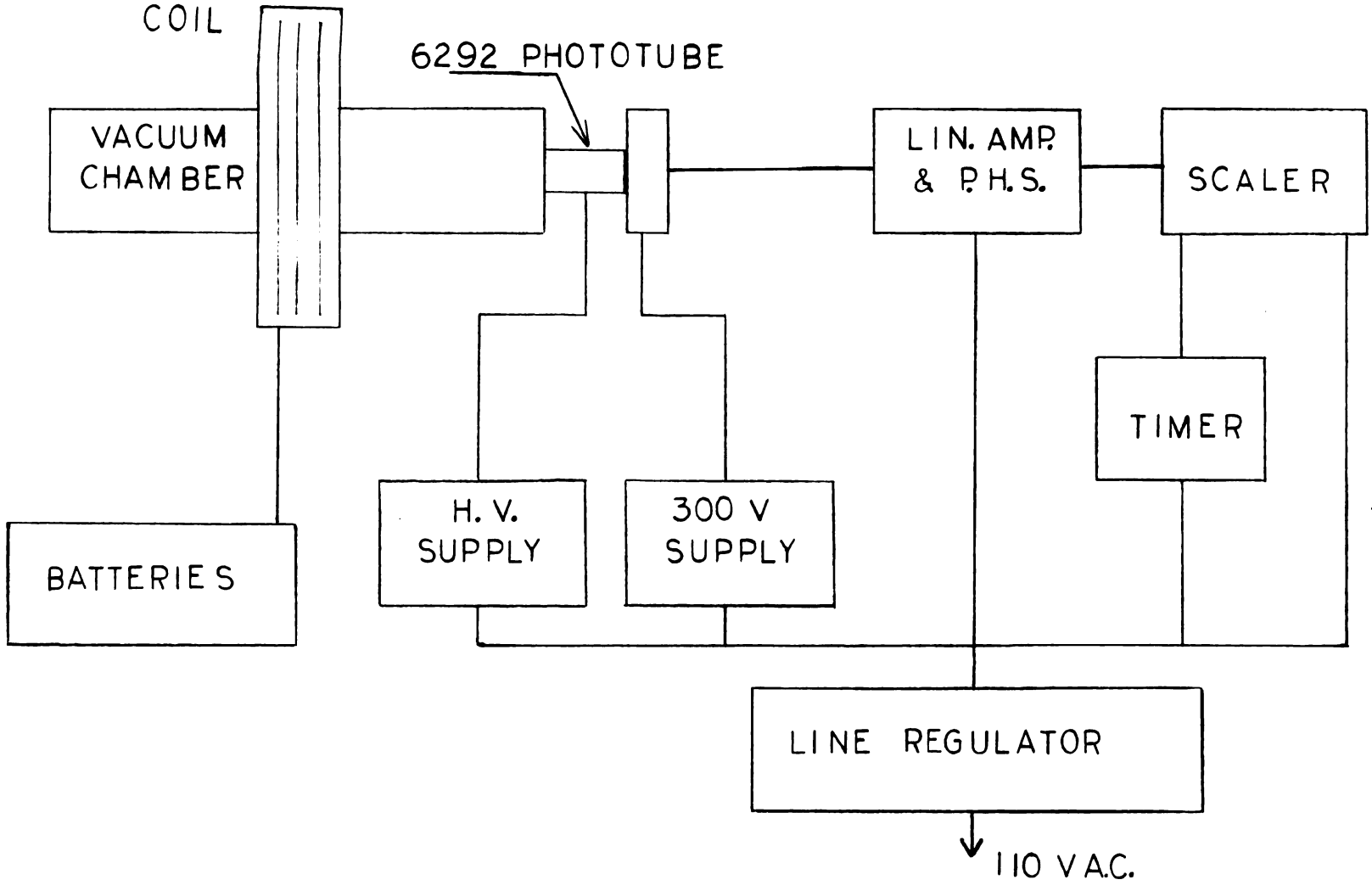

FIG. 3.5 BLOCK DIAGRAM OF THE SPECTROMETER CIRCUITS

3.4 Source Mounting

Figure 3.2 shows the source end assembly. The source holder is located in the center of a four inch brass hemisphere in such a manner that the source will be in the exact center of the hemisphere. This particular design was chosen in anticipation of later conversion to a coincidence spectrometer.

Thin aluminum foil is stretched over the source holder and grounded to the spectrometer chamber. This foil is used as source backing to prevent build up of static charge on the source by the loss of charged particles.

3.5 Detector

The detector end assembly is shown in Fig. 3.3. A scintillation type detector is used to measure the number of particles which are focused on the center region of the detector end. The actual particle detector is an anthracene crystal, one inch in diameter and 1/4 inch thick, mounted on a Dumont 6292 photomultiplier. The crystal is exposed in the vacuum chamber so it is covered with a thin layer of vacuum grease to reduce its rate of evaporation. The external portion of the photomultiplier is attached to a chassis which contains a cathode follower preamplifier. This assembly is fastened to the detector end plate. Figure 3.4 gives the circuit diagram of the preamplifier.

The body of the photomultiplier is wrapped with aluminum foil, which is connected through a 10 megohm resistor to the photomultiplier cathode, to reduce noise pulses due to discharge between metallic shielding and the inner surface of the tube envelope. The photomultiplier is also covered by a mu metal shield and a soft iron pipe to reduce the effects of external magnetic fields on the gain of the tube.

Figure 3.5 shows a block diagram of the spectrometer and the associated electronic equipment. The pulses from the preamplifier are amplified by an Atomic Instrument Co. Model 218 linear amplifier. The linear amplifier also contains a pulse height selector. Therefore only those pulses having amplitudes greater than a predetermined minimum value are selected to drive the scaler. The A. C. line voltage for the electronics is regulated to $\pm$ 0.1%.

3.6 Positioning of the Spectrometer

The spectrometer assembly is mounted on a wooden table. The axis of the chamber is aligned in an approximately north-south direction with the detector at the south end. It is anticipated that at some later date a system of Helmholtz coils will be constructed about the spectrometer to cancel the vertical component of the earth's magnetic field in the region of the chamber. This will permit accurate

determination of the momentum of particles at lower energies than is now possible.

Four positioning screw assemblies are mounted on the two coil end plates in such a manner that these are the only support for the chamber. By the adjustment of these screws the axis of the chamber can be tilted with respect to the axis of the coil. Calibration is provided so that when the chamber is moved it can always be brought back to within $\pm$ 1 mm of its original position.

3.7 Vacuum System

The vacuum pump assembly is connected to the spectrometer near the detector end of the chamber. The pumping system consists of a Consolidated Electrodynamics VMF 80-60 oil diffusion pump and a Cenco Hypervac 20 mechanical backing pump. At least two hours are required to bring the spectrometer to a vacuum of approximately 10^{-5} mm of Hg. The vacuum is measured with an ionization gauge.

3.8 Current Supply

Current is supplied to the field coils by a set of 7 six-volt storage batteries through a circuit shown in Fig. 3.6. The coils are connected in series so the same current flows through each coil. Parallel connection does not yield as good control over the field because then the

current can change from coil to coil. The batteries are connected in series and can supply from 2 to 32 amperes to the circuit through a step switch. Three adjustable resistors provide a continuous current range. The batteries require charging after runs of a few hours duration and this is accomplished by using a D. C. generator. The batteries provide a suitable current supply at values below ten amperes but at higher current readings the current has to be monitored very frequently and the resistors adjusted to keep the field current constant. Much drift is encountered during the first half hour of measurements. This is due mostly to the warming up of the coils. This is partially compensated for by connecting the line D. C. supply to the coils until they are warmed up and then reconnecting the batteries. The current is measured across a 0.001 ohm shunt by means of a Leeds and Northrup Student potentiometer with a sensitive General Electric galvanometer as a null detector. The current can be controlled to only $\pm 2.5\%$ with the present power supply. A much better controlled power supply is to be used in future work.

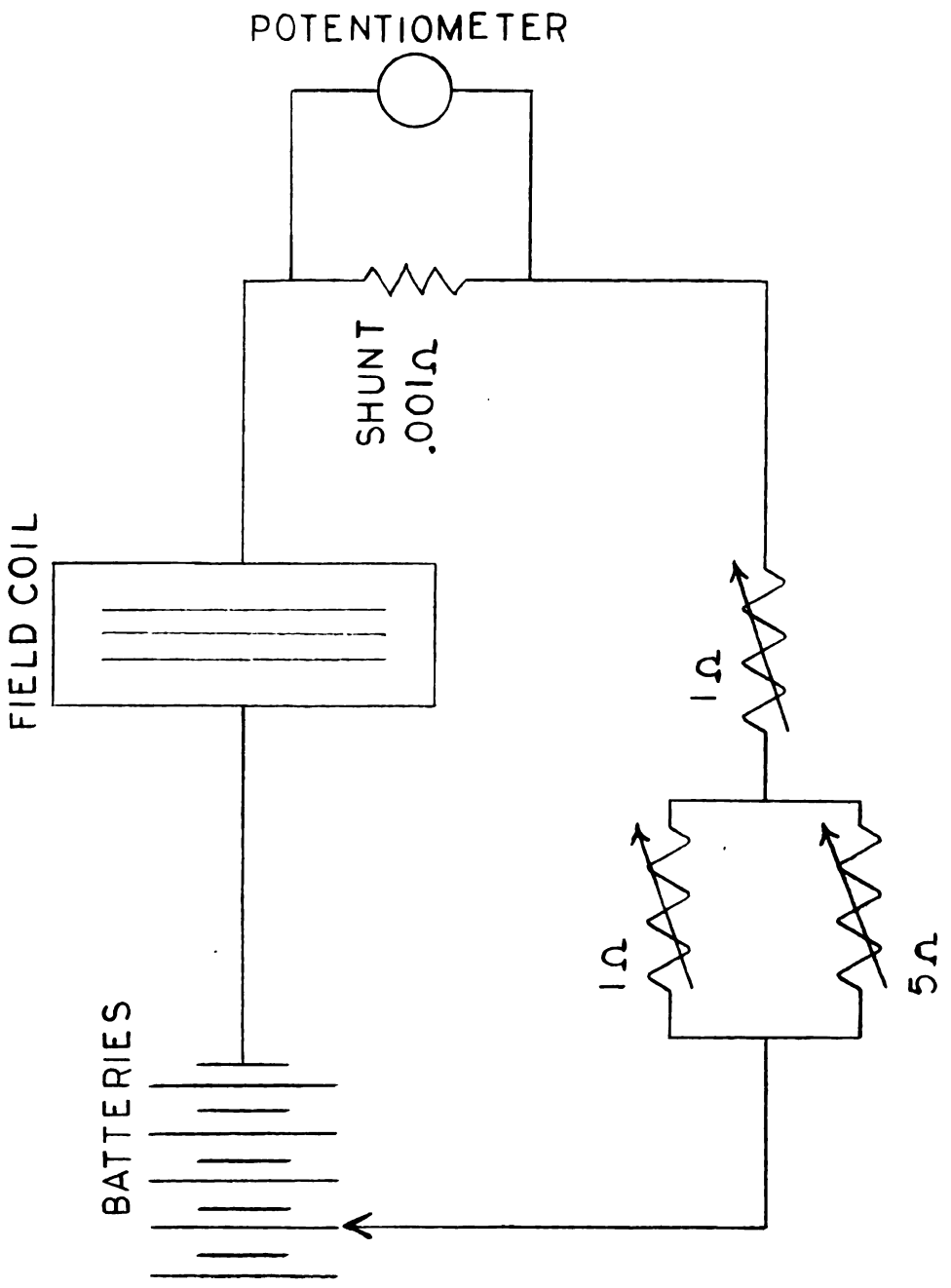

FIG.3.6 SPECTROMETER CURRENT SUPPLY CIRCUIT

CHAPTER IV.

MEASUREMENTS WITH THE SPECTROMETER

4.1 Alignment of the Spectrometer

In all thin lens spectrometers the source, the baffles and the detector must be accurately centered with respect to the symmetry axis of the magnetic field. This adjustment is of critical importance for achieving suitable resolving power and accurate calibration of the instrument. In the spectrometer described in this thesis, the source, detector and all baffles are permanently centered with respect to the axis of the spectrometer. The chamber, in turn, is suspended within the field coil. Rough alignment may be obtained by visual measurement but final adjustment is best obtained by observing the intensity of a monoenergetic spectral line. A source of cesium 137 was used for the purpose of obtaining the alignment, resolution and calibration of the spectrometer.

The movable baffles were spaced 3.5 inches apart and in their approximately correct positions by the assumption that the particle paths are nearly straight lines outside the region enclosed by the coil.

As the current in the coil was varied, the counting

rate divided by the current was noted and plotted*. The general shape of the cesium 137 electron spectrum was recognized. The current was then set at a value which focused the conversion line of 623.8 kev. The axis of the chamber was then tilted with respect to the axis of the coil by the adjusting screw until the maximum counting rate was attained. The current was again set for a maximum counting rate and the chamber realigned. In this way the image of the source was focused by the lens directly on the crystal. It was noted that the sharpness of the line was very sensitive to this alignment. The shape of the line was determined and a resolution of approximately 3.6 percent was found. That is to say, the $\Delta H\rho$ corresponding to the width of the line at half-height was such that:

$$\frac{\Delta H\rho}{H\rho} = 0.036$$

Figure 4.1 shows the cesium 137 electron spectrum as a function of the current. The poor stability of the power supply did not allow points to be measured on the sides of

*There is a linear relation between the current and the field intensity, therefore the momentum of the particles focused is also linearly related to the current. However, the momentum width of the range of particles focused also varies directly with the field current. Therefore, to plot the momentum spectrum it is necessary to plot the counting rate divided by current against current.

the conversion lines although the spectrometer is capable of resolving both the K and L lines of cesium 137 as shown in Fig. 4.1.

4.2 Calibration of the Spectrometer

In any spectrometer with a uniform magnetic field, an absolute determination of the momentum corresponding to a given spectral line can be obtained by means of geometrical measurements in order to determine the radius of curvature, ρ, of the central path, and magnetic measurement to determine the field, H. These quantities are related by the formula

$$p = H e \rho$$

where e is the electron charge in absolute e.m.u. The quantity commonly measured in nuclear spectroscopy is the magnetic rigidity or momentum, p',

$$p' = \frac{p}{e} = H\rho$$

where p' is expressed in gauss-centimeters.

This method of absolute determination of the momentum is impossible in the case of the thin lens spectrometers

where the field is non-uniform and the electron paths are only known approximately. The method used in this case is to determine the momentum of an internal conversion line of known energy. Since the quantity actually measured is the current producing the magnetic field, the relation between current and field must be known. In the iron free spectrometer the relation between current and field is linear.

The spectrometer was calibrated against the 623.8 kev. K conversion line of cesium 137. This corresponds to a magnetic rigidity of 3381 gauss-centimeters. The value of the field current at this momentum was found to be 14.0 amperes. This gives a constant for the spectrometer to be approximately 242 gauss-centimeters per ampere.

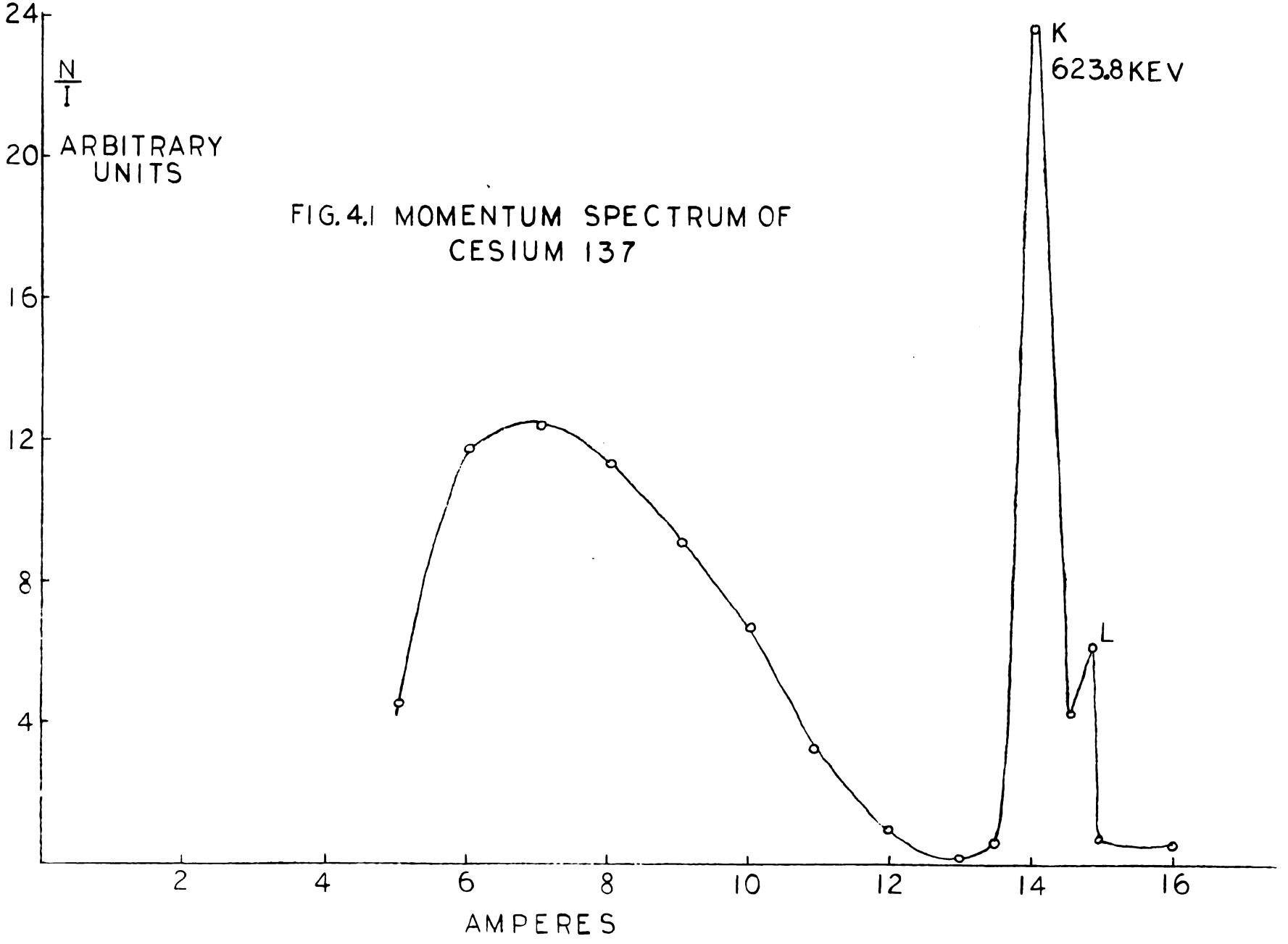

FIG. 4.1 MOMENTUM SPECTRUM OF CESIUM 137

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