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NUCLEAR ENERGY LEVELS BY ABSOLUTE MAGNETIC ANALYSIS
OF INELASTIC PROTON SCATTERING

by

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I. INTRODUCTION

The measurement of the excitation energies of the states of nuclei is a problem to which a large amount of effort has been applied in recent years. Experiments and techniques of varying degrees of accuracy have been developed for many of the numerous possible reactions which yield information on the energies of these states. These techniques and instrumental approaches are not in general of universal applicability. For instance, the energy measurements for charged particles, neutrons, electromagnetic quanta, and beta particles in general require different methods for optimum results. However, a common feature of most precision experiments is either the direct utilization of magnetic or electrostatic analysis or the use of a calibrated standard determined by these means.

This success of magnetic and electrostatic analysis in determining the energies of charged particles probably lies chiefly in the fact that such determinations may be made in terms of readily measured quantities. In the case of a magnetic field, a charged particle of constant mass and speed, when traveling in a uniform magnetic field, will describe a circular trajectory, the radius of which is proportional to the momentum of the particle and inversely proportional to the particle charge and the strength of the magnetic field. Furthermore, a geometrical property of the circular trajectories results in a focusing effect, such that a monoenergetic group of particles, originating from a line
parallel to the field and emitted within a limited solid angle, will be focused (to within second order effects) into a line, after having traversed half a circular orbit. It is then possible, for a particle of a given charge and mass, to measure the momentum with an accuracy limited only by the accuracy of the measurements of length and of magnetic field; both of these quantities are susceptible to measurement with considerable precision.

In particular, magnets of the annular type afford a geometry which tends to maximize the potentialities for accurate measurement of the radius of curvature and field strength. By confining the usable field to a ring-shaped region near the outer diameter of the pole pieces, a maximum diameter may be obtained with a minimum expenditure of power. As the absolute errors in the radius measurement are essentially of the same magnitude as would arise in the measurement of a smaller radius, the relative error in the radius measurement is less than that which would result with a smaller radius. The use of a large radius also permits the use of moderate fields for the range of particle energies studied, thereby producing a more uniform field.

The measurement of magnetic fields was greatly simplified with the development of the proton moment magnetometer. This instrument, through the Larmor procession of the proton moment in a magnetic field, reduces the measurement of field strength to a determination of the frequency of the proton procession. The measurement of the momentum, and thus the energy, of a given particle is therefore reduced to a length and a frequency and constitutes an
absolute measurement independent of all calibrations except the standards of length and time.

When a magnet of the annular type is used to measure the energy of particles emitted from naturally radioactive nuclei, such as alpha particle emission from heavy nuclei, the situation is particularly simple. The radioactive sample must be localized within fairly narrow limits by placing slits in front of it; the solid angle of acceptance must be set by slits to confine the accepted particles to a uniform portion of the magnetic field; and a suitable detector with proper localization in space must be placed to intercept the particles as they come to a focus after having traversed half their circular orbits.

This situation becomes somewhat more complicated when a charged particle induced reaction is considered. In this case a beam of monoenergetic particles must be directed into a magnetic field so as to strike a target of the nuclei to be studied at the position occupied by the radioactive sample in the example above. The magnetic field may then be adjusted to bring to focus at the detector various groups of particles emitted by the excited nuclei of the target. Consideration of the general classical non-relativistic treatment of such a two-body reaction indicates that:

\[ E_2 = \frac{m_0 m_3 + m_1 m_2 \cos 2\Theta}{M^2} E_1 + \frac{m_2}{M} Q \quad (I-1) \]

\[ + \frac{2 m_2}{M} E_1 \cos \Theta \left\{ \frac{m_1 m_3}{m_2 M} \left( \frac{Q}{E_1} + \frac{m_0}{M} \right) - \frac{m_1^2}{M^2} \sin^2 \Theta \right\}^{1/2} \]
where \( E_2 \) and \( E_1 \) are the energies of the observed and bombarding particles, respectively; \( Q \) is the energy release of the reaction which is the energy equivalent of the mass lost in the reaction; \( m_0 \), \( m_1 \), \( m_2 \), \( m_3 \) and \( M \) are, respectively, the masses of the target nucleus, bombarding particles, observed particle, residual nucleus, and the compound nucleus; \( \Theta \) is the laboratory angle between the directions of motion of the bombarding and observed particles.

The purpose of magnetic analysis of such a two-body process is generally the determination of the quantity \( Q \). In terms of the other quantities, this relation may be stated explicitly:

\[
Q = \frac{m_2 + m_3}{m_3} E_2 - \frac{m_3 - m_1}{m_2} E_1 - \frac{2}{m_3} \left( m_1 m_2 E_1 E_2 \right)^{1/2} \cos \Theta
\]  

The \( Q \) values obtained from the above relation may serve in several useful capacities: first, in reactions where \( m_1 \) and \( m_2 \) are particles of different types, the \( Q \) value for transition to the ground state of the residual nucleus may be obtained if the bombarding energy, \( E_1 \), is known independently. The difference in the rest mass of the two nuclei concerned may then be computed from this \( Q \) value. If cycles of such related nuclei are considered, the mass of these nuclei may be specified with relationship to one member of the group (\( O^{16} \) is the basis of the usual atomic mass unit scale).

Secondly, in reactions where \( m_1 \) and \( m_2 \) are different, if particle groups are observed corresponding to the residual nucleus being left in excited states, then subtracting the \( Q \) value
of this group from that obtained from the ground state group yields
the energy of excitation of the state. Again the bombarding
energy must be independently known, or if the ground state Q value
is known accurately enough from other measurements, $E_1$ may be
calculated from the observed ground state Q.

Thirdly, if the observed and bombarding particles are
identical the process is known as scattering. Elastic scattering
occurs if no energy is lost to the excitation of the target nucleus,
and inelastic scattering occurs if energy is given up to the nucleus
exciting it to a state other than the ground state. In this case,
since $m_1 = m_2 = m$, and $m_0 = m_3 = M$, Equation (I-2) takes the form:

$$Q = \frac{M+m}{M} E_2 - \frac{M-m}{M} E_1 - \frac{2m}{M} (E_1 E_2)^{1/2} \cos \Theta$$

(I-3)

In the elastic case Q is equal to zero, since no energy of excita-
tion is imparted, and the rest masses of the two interacting nuclei
are the same before and after interaction. Thus, the energies $E_1$
and $E_2$ are related only as a function of the masses and the angle $\Theta$.
Therefore, from an elastically scattered group the bombarding
energy, $E_1$, may be calculated, and no independent measurement of
this quantity is required. Then, with the bombarding energy known,
the Q value for an excited state may be calculated from the observed
$E_2$ for that group, and this Q value is the value of the energy of
excitation of the state.
Since this type of experiment permits self-calibration of the bombarding energy, inelastic scattering provides an extremely accurate means of finding the excitation energies of the states (near the ground state) of stable nuclei. For this reason, the experiments described in this thesis were of this type and the subsequent discussion will be chiefly concerned with the scattering problem.

Now, it will be noticed from Equation (I-3) that the angle $\theta$ enters into $Q$ value relation as $\cos \theta$; thus any error in $\theta$, whether due to the difficulty of measurement or to the finite acceptance angle required by the spectrometer, will have the greatest effect if $\theta = 90^\circ$ and the least at $\theta = 0^\circ$ and $\theta = 180^\circ$. The use of $\theta = 0^\circ$ is impractical, but the $180^\circ$ geometry has decided advantages both as to accuracy and other factors.

Since it is not always practical, or indeed worth the difficulty involved, to direct the beam to the target at exactly $180^\circ$ from the mean acceptance orbit of the spectrometer, a method is necessary for correcting the energy $E_2$, observed at some angle $\theta = 180^\circ - \alpha$ (where $\alpha$ is small), to that which would have been observed at $\theta = 180^\circ$. Such an energy correction may be found from the $Q$ value equation:

$$ (\Delta E_2)_\alpha = \frac{2 E_2 \alpha^2}{1 + \frac{M+m}{m} \left( \frac{E_2}{E_1} \right)^2} $$  \hspace{1cm} (I-4)

This expression is independent of the $Q$ value and hence applies with equal validity to both elastic and inelastic groups.
Under the condition, $\theta = 180^\circ$, the expression relating the 
$E_1$ and $E_2$ for elastic groups takes on a simple form

$$E_2 = \left( \frac{M - m}{M + m} \right)^2 E_1$$  \hspace{1cm} (I-5)

and for the inelastic groups

$$E_2 = \frac{M^2 + m^2}{(M + m)^2} E_1 + \frac{M}{M + m} Q$$  \hspace{1cm} (I-6)

$$+ \frac{2m}{M + m} E_1 \left\{ \frac{M}{M + m} \left( \frac{Q}{E_1} + \frac{M}{M + m} \right) \right\}^{1/2}$$

The relationship expressed by Equation (I-5) not only
serves to define the bombarding energy, but also by the agreement of
values of $E_1$ so determined, establishes the masses (i.e., the identity)
of the nuclei responsible for the various elastic groups present,
and thereby serves to distinguish weak elastic groups from the
inelastic groups of interest. Furthermore, from the nature of the
dependance of $E_2$ on $E_1$, in Equation (I-6), it may be seen that at
two different bombarding energies there will be a change in the
difference between the $E_2$ of an elastic group from one type of
nuclei and the $E_2$ of a group from nuclei of different mass. This
change, reflected in the agreement, at two or more different
bombarding energies, of a $Q$ value for an excited state in a given
nucleus, is sufficient proof of the existence of such a state in this
nucleus. This method of analysis therefore provides a positive
identification of the nuclear species to which an observed group
is to be ascribed.
The detection of groups of particles with momenta less than that of the bombarding particles, such as is required in an inelastic scattering experiment, presents difficulties not necessarily encountered in experiments of the other two types considered earlier. This situation imposes the very stringent requirement that only an extremely small fraction of the particles of the incident beam may be allowed to strike materials (other than the target) in the vicinity of the target such that they may be scattered into the acceptance angle of the spectrometer. When a portion of the beam is allowed to strike materials which are thick with respect to the particle range, a continuous background will be presented at the detector. This background, if it is of sufficient magnitude, will make the detection of weak groups impossible.

Since the Rice magnet had not been used for experiments of this type before the experiments reported herein were attempted, much of the recent instrumentation has been concerned with the problem of background removal. The extensive slit systems and techniques utilized are described in detail in later chapters.

Although the $\theta = 180^\circ$ geometry increases the accuracy available and helps the background situation (at least as far as coulomb scattering is concerned), it presents some difficulties. Under this condition the incident beam must travel through a considerable region of strong field in the magnet gap. Thus, at constant bombarding energy, the incident beam trajectories will take on different radii of curvature at the different field strengths necessary to study the spectra of observed particles.
Since the angle $\Theta$ is to be kept near $180^\circ$, the asymptotic direction of the incident beam changes for different field settings of the magnet. For this reason, it was necessary to equip the magnet with several degrees of freedom of translation and rotation. Then, for any given field setting the magnet may be moved to accept the beam at the target at the proper angle. The instrumentation and techniques associated with this problem are discussed in detail in later chapters.

In addition to the problems concerning the possibility of accurately measuring the excitation energies of nuclear states by magnetic analysis of inelastically scattered particles, the question of the facility of such measurements should be considered. In this connection the particle detection system has been designed to produce maximum information in minimum accelerator time. The use of photographic emulsions permits the examination at one time of a portion of the spectra of 15 mm from a diameter of curvature of about 700 mm. This may be contrasted with a maximum of 1 mm which could be obtained with a counter (such as a gas filled proportional counter) with limited aperture.

From the foregoing discussion the simplicity of principle under which magnetic analysis operates is apparent. However, the precision with which such absolute measurements can be made requires a considerable attention to detail. This detail is the subject of concern in the three succeeding chapters on apparatus and techniques. Following these, the result of three series of experiments performed with the magnet are presented. It is hoped that in addition to
the fundamental nuclear information which they contain, they may
serve as examples of the capabilities and limitations of the Rice
Institute annular magnet in its current state of development.
II. APPARATUS

Magnet

The annular magnet\textsuperscript{1} and its base are shown in the photograph of Fig. 1. The internal construction of the pole pieces is indicated in the drawing of Fig. 2, which is a cross section in a vertical plane containing the symmetry axis. The circular and annular shims between the pole pieces in the core define the separation of about .56 inches at the annular gap. These shims may be adjusted to control the inhomogeneities in the field around the gap. The gap itself is 5 cm wide with a mean radius of 35 cm.

Four annular coils each of about 1400 turns of $\#14$ wire surround the core. Each coil has individual electrical and water-cooling connections which are brought out through the gap in the unused half of the annulus. With the water-cooling, the coils can dissipate about 3 KW of power which will produce a magnetic field of approximately 15 kilogauss, which essentially saturates the magnet iron. For the proton inelastic scattering experiments described in this work, fields of not over nine kilogauss were required with the maximum bombarding energy available.

The lower pole piece rests on a ring of brass ball bearings (one inch in diameter) which run in a groove in the stainless steel base plate. A rack and pinion equipped with a ratchet produces rotation of the pole pieces about their symmetry axis. A cam system, driven by external handles, permits raising the pole pieces off the ball bearings when the magnet is to be moved or otherwise handled.
in a manner which might produce damage to the bearings. The non-magnetic bearings and base plate are necessary to reduce flux leakage to the base.

Translation of the magnet is accomplished by sliding the base over the large flat surface of the sub-base. The base is equipped with three oiled brass footplates which slide with relative facility over the ground surface of the sub-base. Two mutually perpendicular pairs of lead and lag screws are provided to produce this translation.

The sub-base is considerably over-designed for strength, in order that there will be no appreciable deflections of the ground plate under the influence of the weight of the magnet. The plate is one-inch-thick steel supported by a network of six inch "I" beams. The hexagonal shape was chosen for the convenience of the three point support provided by either the wheels or the elevating jack screws. These screws were supplied to raise the height of the magnet gap to that of the emergent beam of the accelerator.

The magnet is thus provided with rotation about a vertical axis and three degrees of translational freedom. Such freedom is sufficient to satisfy the conditions mentioned in the introduction.

Field Regulation and Detection

The field regulation system used for the earlier experiments, described by Jones\(^2\), utilized the proton moment absorption signal both for detection and to provide the error signal for the
current through the magnet. This system proved in practice to provide regulation characteristics somewhat less stable than desirable. For this reason the system was recently changed to one of a standard current regulator with the proton moment device retained for detection and monitoring of the field.

Fig. 3 is a block diagram of the electrical system. The current provided by a three kilowatt D.C. motor-generator passes through a water-cooled standard resistance, A, placed in series with the magnet coils. The potential difference produced across this resistance is balanced against that produced by the setting at the Helipot, C. Any unbalance changes the potential from that set by the Helipot in the balanced condition. This potential is amplified with a D.C. amplifier and placed on a grid of the current regulation tubes. These tubes control the current through the exciter coils of the generator, and thus the current output of the generator. Therefore, when an unbalanced condition exists, the bias set by the Helipot is altered, changing the current through the standard resistance to restore the balanced condition.

Although such a system has proved to be more satisfactory for regulation of the field, the proton moment magnetometer still provides the best means of setting and monitoring the field, since this device is independent of hysteresis and thermal effects.

The proton moment device used with the annular magnet utilizes a series of three probes, each containing an R.F. coil of different inductance, in order to provide a suitable frequency range. These combinations produce frequencies from 14 to 42 M.C./sec,
which correspond to a range of .8 to 6 Mev for protons with the 35 cm radius of curvature of the mean radius of the magnet.

The frequency of the oscillator is set by comparison with a harmonic of the output of a surplus U.S. Army Signal Corps signal generator. The beat notes between the two signals are presented on an oscilloscope, thus providing a visual indication of the difference in frequencies. At each frequency setting the signal generator is calibrated against an internal crystal. For the signal generator used with the annular magnet, no detectable difference has been found between the crystal frequency and the standard frequency broadcast by the National Bureau of Standards Station WWV.

The probes, placed in the uniform portion of the field of the annular gap, consist of a hydrogensous sample placed within an R.F. coil. A Helmholtz coil modulates the field experienced by the proton moments, sweeping their precessional frequency through that of the R.F. field twice a cycle of the modulating field. This produces an absorption of energy from the oscillator which appears as a signal on the oscilloscope. The strength of the field at the position of the probe may thus be determined from the frequency of the oscillator when the absorption signals appear in the center of the oscilloscope trace.

**Vacuum Tube**

The target, detector, and associated slits are contained in a "C" shaped vacuum chamber which slips into the gap of the magnet. This apparatus is shown in Fig. 4, which is a cross sectional
view in the mid-plane of the gap.

The basic tube is a two-inch-diameter copper tube, bent to a semicircle to fit the gap, and flattened to approximately one-half inch in height. Openings were cut at positions near either end of the tube and flanges silver-soldered into place. The faces of the flanges were then accurately milled with respect to each other to assure the alignment of the apparatus bolted to them. Various pieces of apparatus may be inserted through the flanges and a vacuum seal made with "O"-ring gaskets against the flanges.

The material projecting into the lower left hand corner of Fig. 4 is the tubing used to join onto the accelerator vacuum system. The beam from the accelerator passes through this tubing, a flexible metal bellows, and into the entrance port of the vacuum tube. The slits at A, external to the magnetic field, are used to collimate the entering beam. Two pairs of slits, vertical and horizontal, are placed on rods which pass through Garlock-type vacuum seals, thus allowing adjustment of the slit width and position from outside the vacuum. A viewing quartz, B, is similarly mounted and may be inserted for the adjustment of the slits A, or withdrawn to pass the beam.

**Target Assembly**

Upon entering the magnet gap the beam passes through the traveling slit, C; the target slits, D; the target foil, E; and finally is collected at the Faraday Cup, F. These pieces of apparatus are shown in the photograph of Fig. 5, which depicts the internal relationships of these members of the target group.
Fig. 5
The traveling slit, C, is driven through a Sylphon bellows by a micrometer screw graduated in one-thousandths of an inch. The slits are of tantalum and the rod connecting their assembly to the micrometer consists of two concentric pieces of tubing which provide air-cooling to the slit assembly. The slits and micrometer system are electrically insulated from the tube by a glass spacer. This permits direct measurement of the amount of beam striking the slit.

The targets, which for proton inelastic scattering must be thin foils, are each mounted on a target carrier. These carriers may then be mounted at position E of the target holder. This arrangement assures that the target foils will be accurately aligned with respect to the target slits, since all target carriers are carefully machined to close tolerances. In position, the carrier holds the foil .030 inches behind the plane of the target slit edges. The slot in the carrier over which the foil is mounted, and through which the beam passes, is sufficiently wide to overlap the slit edges by .5 mm, such that no beam passing through the target slit may strike the carrier itself.

The target slits, also of tantalum, are rigidly attached to the target holder. The outboard (away from the center of the magnet) slit is adjustable in order that the width of the target slits may be adjusted as desired. However, the inboard slit must remain fixed, since the radius of curvature measurement depends upon its position. In use, both slits are generally covered with a thin coating of zinc sulfide in order that they may fluoresce when struck
by the beam. The port at G is provided for viewing these slits in the beam alignment procedure described in Chapter III.

The Faraday Cup at F is carefully positioned so that it will intercept the incident beam over the complete range of radii of curvature, (10-100 cm) that may be expected in the use of the magnet. However, it is located so that none of the acceptance orbits of the spectrometer intercept the cup. Thus, for a particle striking the cup to be accepted by the spectrometer it must be scattered twice: once from the cup and then again from the portion of that wall of the vacuum tube which is within the limits of the acceptance orbits of the spectrometer. The probability for the occurrence of these two successive events should be small enough that the contribution to the background from this source is negligible.

The inside of the vertical walls of the cup is lined with tantalum sheet and air-cooling tubing surrounds the outside of the walls. The cup must be completely insulated, since the beam which it collects must be integrated to find the number of particles striking the target. In fact, the leakage path to ground must be no less than about $10^{10}$ ohms to assure proper operation of the beam integrator. The cup is supported by the air-cooling tubes which are led in through the end plug of the tube by two large Stupakoff seals. The top and bottom of the cup are separated from the vacuum tube by a thin sheet of teflon.

The anti-scattering partition at H is placed to prevent direct entry into acceptance orbits of particles scattered from the
traveling slit. The slits around the tube were inserted to prevent the acceptance of particles singly scattered from areas other than those in the vicinity of the target, and to greatly reduce the probability of particles reaching the detector which have been multiply scattered from the walls. This is particularly true in the vertical direction because of the proximity of the top and bottom walls of the vacuum tube. For this reason, only the central three millimeters are used of the total of about nine millimeters of vertical height available within the tube. In order that the slit J, at 90°, define the solid angle and acceptance angle of the spectrometer, the other slits around the tube have widths about one millimeter larger than calculated to contain the extreme orbits accepted by slit J.

**Detector System**

The detector, shown in the upper portion of Fig. 4, and in the photograph of Fig. 6, is essentially a camera equipped to successively rotate nuclear emulsion plates into position for exposure, and to control the time of the exposure with a shutter. The plates are mounted, with an inclination of 12.5 degrees to the beam, on the roughly octagonal table shown in Fig. 4. This table may be rotated without disrupting the vacuum of the system to present the plates for exposure at the position K. This rotation is accomplished by the rather complicated system of bearings and an eccentric crank driven through a Sylfon bellows. These appendages are evident in the lower portion of the photograph. The table is locked into position by a drill rod, through the top of the camera,
which engages a hole in the table when it is in the proper position. The shutter, which closes the opening at L, is driven in a slot by a rack and pinion, which is controlled from outside the vacuum by a bellows - crank arrangement similar to that used to drive the table. An inner light-tight box (not shown in Fig. 6) is provided to permit transfer of the camera from the dark room, where the plates are loaded, to the magnet.

The device at M in Fig. 4 serves to project a line onto the inboard edge of the plate while it is being exposed to particles. A fine straight wire filament of the bulb is imaged by the lens of the system to a line approximately 0.1 mm wide on the plate, about 1.5 millimeters from the inboard edge. This indexing is necessary to the radius of curvature measurement.

More detailed drawings of the camera are available in the author's M.A. thesis⁵.
III. PRIMARY MEASUREMENTS

The three directly measurable quantities of primary importance in the determination of a Q value are the radius of curvature, the strength of the field (in terms of frequency), and the angle $\Theta$ between the directions of the incident and observed particles. The kinetics, discussed in the introduction, indicate that the momentum of a particle is given by a constant times the product of the radius of curvature and the frequency of the proton moment precession. The energies, $E_2$, are then, with relativistic correction, proportional to the square of the momentum. The angle $\alpha$, the deviation of $\Theta$ from 180°, was introduced as a correction to $E_2$ to permit the use of the Q value equation for $\Theta = 180^\circ$. Since the validity of the experiments described in this thesis depends so strongly upon these measurements, this chapter considers in detail the methods of measurement and their reliability.

**Radius of Curvature**

For a given group of particles accepted at the detector, the diameter of curvature is considered (for the purposes of measurement) to be the sum of three separately determined parts. These parts, all measured along the focal diameter of the magnet, which passes through the plane of the target slits and through the detector, are: $\Delta R_o$, the distance from the inboard edge of the beam to the inboard edge of the target slit; $2R$, the distance from the inboard edge of the target slit to the light line (indexing mark projected by the
optical system onto the edge of the plate -see Chapter II); and, \(X_0\), the distance from the light line to the particle group on the photographic detector plate.

**The Distance \(\Delta R_0\)**

The procedure of aligning the incident beam on the target must be considered in order to ascertain the distance \(\Delta R_0\). The drawings of Fig. 7, and reference to the apparatus shown in Figs. 4 and 5 will assist in the explanation of this procedure.

The external slits, A (Fig. 4), are first adjusted, with the aid of quartz B, to bracket the most intense portion of the focused beam. A width of about 2 mm of the beam spot on the quartz, is obtained. The quartz and the traveling slit, C, are then withdrawn and the beam allowed to strike the target slits. The magnet is translated on its sub-base until the fluorescence of the beam is seen to equally bracket the opening of the target slits. This situation is shown in (a) of Fig. 7. The traveling slit is then moved in to the point where the fluorescence disappears on the outboard slit, as in (b), and to the point where it begins to appear on the inboard slit, as in (c). The micrometer readings \(R_1\) and \(R_2\) are taken at these points.

The micrometer is then set such that the beam is allowed to pass through the center of the target slit, as in (d). The external slits are adjusted to reduce the size of the beam sufficiently that one percent or less of the beam passing through the target strikes the traveling slit (as shown in (e)). The amount of beam
striking the traveling slit and the target are determined by microammeter readings of the currents from the traveling slit and Faraday cup, respectively. The inboard and outboard edges of the beam, at the traveling slit, are then determined as in (f) and (g), where the micrometer readings are \( R_3 \) and \( R_4 \), respectively. The criterion for the edge of the beam is arbitrarily defined as five percent of the beam, where the beam current measurement techniques are as above.

The desired distance between the edge of the beam and the inboard edge of the slit, \( \Delta R_0 \), would then appear to be the distance which the traveling slit moved between defining these two points. This distance is the difference, \( \Delta R \), in the micrometer readings, where \( \Delta R = R_2 - R_3 \). However, this distance is measured at the traveling slit and is not the desired distance at the target slit, since the beam suffers a convergence in passing through the magnetic field between the traveling and the target slits.

A discussion of this convergence effect is contained in the Appendix, where a relation for the amount of convergence of the beam is found to be

\[
\delta R = \left( \frac{w_2}{w_1 + R_2 - R_1} \right) \Delta R , \quad (\text{III-1})
\]

where \( R_1 \) and \( R_2 \) are the micrometer readings defined in Fig. 6, and \( w_1 \) and \( w_2 \) are the measured widths of the traveling slit and target slit, respectively. The distance, \( \Delta R_0 \) then becomes

\[
\Delta R_0 = \Delta R - \delta R . \quad (\text{III-2})
\]
It may be seen that the edge of the beam could be most easily and accurately defined directly by the edge of the target slit, as in Fig. 7(a). However, this requires that a portion of the beam be allowed to strike the target slit; and, since the edges of the target slit lie within the acceptance angle of the spectrometer, such a course is impossible for experiments in which it is desired to detect particles with momenta less than that of the incident beam.

A second possibility, which was utilized in the earlier fluorine experiments (Chapter V), is to allow the traveling slit to define the edge of the beam directly, as in (d) of Fig. 7. However, this requires that a portion of the beam strike the traveling slit. Under these conditions a significant amount of the beam is deflected by small angle scattering onto the target slits, thereby producing background at the detector. It was found that by reducing the amount of beam striking the traveling slit to one percent of that detected at the Faraday cup, the background was reduced by at least an order of magnitude from that obtained under the situation (d). For this reason the more elaborate technique was used for the beryllium and scandium experiments.

Although this technique is less accurate in defining the radius, because of the inherent difficulties in defining the edge of the beam, such experiments as those conducted with scandium would not be possible at all unless such measures were taken.

An estimate of the accuracy with which \( \Delta r_0 \) may be measured is provided in the Appendix, where an attempt is made to
fit the observed phenomena to theoretical curves. This material indicates that a probable error of ± 0.004 cm should be assigned to $\Delta R_0$ for a given measurement.

**The Distance 2R**

The length between the inboard edge of the target slit and the light line is measured by direct comparison with a secondary length standard. This standard consists of a .5 inch diameter invar bar 28 inches long with a flat surface milled on the top for one inch from either end and a flat surface milled on the bottom one fourth of the length from either end. The bar is always supported on knife edges on the bottom flat surfaces in order to reduce the effect of a gradual yielding of the bar under its own weight. The temperature coefficient of the invar bar is sufficiently small that changes in its length are negligible compared to other errors for the range of room temperatures in which the bar was used.

Two scribe marks, one longitudinal and one transverse, were placed on the top surfaces at either end. The distance between the intersection of these two lines on either end was measured by comparison with a half-meter bar calibrated by the National Bureau of Standards.

The comparison of the distance 2R with the length of the standard bar is made on a comparator specially built for this purpose. The comparator consists of an old lathe bed which was equipped with a table to support the tube or standard bar and two rigidly mounted traveling microscopes. The table is circular with a diameter
equal to that of the outer diameter of the magnet gap. Thus, an attempt is made to place the tube for measurement under the same stresses due to its own weight, as it experiences in use with the magnet.

A slot is cut in the top of the table to accommodate the standard bar in such a way that the surfaces on which the reference lines are scribed are at a prescribed height above the surface of the table. This height corresponds to the vertical center of the tube when it is in position on the table. Thus, when the microscopes are focused for the surfaces of the standard bar, they will automatically give a focus at the center of the slits to be measured in the tube.

The two microscope carriages are attached to the heavy horizontal member of the lathe bed at positions near the edges of the table. This mounting is sufficiently rigid that adjustment of the position of the microscopes on the carriage does not disturb the relative positions of the carriage scales by any amount detectable by successive measurements of length of the standard bar. The distance between the scribes on the standard bar was set close enough to the length 2R that translations of the microscopes for distances of less than one millimeter are required for the comparison. The carriage scales were calibrated against the N.B.S. calibrated standard and showed no detectable difference from the standard for one millimeter intervals. The micrometer dials of the carriages are graduated in five micron intervals.

In order that a direct comparison of the bar and tube be
possible, .25 inch diameter holes were cut in the top of the vacuum tube directly over the inboard target slit edge and over the intercept of the light line and the focal diameter. These holes were flanged to permit the insertion of thin brass disks which were sealed in position with a low-melting-point wax in order to allow evacuation of the tube.

The edge of the inboard slit is determined by inserting a fine wire through the hole in the top of the tube and pressing it against the edge of the slit. The wire is adjusted vertically to achieve a sharp focus in the microscope of the horizontal section of the wire as it rests against the slit edge. This procedure assures measurement of the slit at its vertical center. Illumination is provided for this measurement by a small bulb inserted through the entrance port of the tube and positioned near the slits.

The faint light of the light line, projected at the detector, is made visible by placing a mirror on a dummy plate in position K with the mirror inclined to reflect the light rays into the microscope. This microscope is equipped with two cross hairs of apparent separation slightly greater than the apparent width of the light line. The alignment of these cross hairs to bracket the light line is considered to be more accurate than alignment to split the light line with a single cross hair.

In practice, four successive readings are taken of the scribe marks on both ends of the bar, and of the two points of the tube. The average deviations of these four readings provide an estimate of the accuracy with which they may be made. From the data
of several recent measurements the average deviations from the means were found to be ±.0003 cm for measurements of the scribe lines of the standard bar and ±.0006 cm for measurements of either the slit edge or light line. Since each of these measurements is independent, the error expected in a comparison of the bar and tube should be of the order of ±.0010 cm.

Although this error in measurement is small (a relative error of only ~1.5 x 10⁻⁵), it cannot be considered as the only error in the specification of the quantity 2R. Since it is impossible to make this measurement with the tube in place in the magnet, under the conditions in which the plates are exposed, the question arises concerning the validity of the assumption that 2R is the same under experimental conditions as under the measurement conditions.

In an effort to realize this condition a number of steps are taken. The gap width of the magnet has been set sufficiently wide that no binding occurs when the tube is inserted into the gap. With the camera end of the tube free, the tube is bolted rigidly to the magnet at the flange of the entrance port. Support at this point is necessary to minimize the effects of the resultant force of atmospheric pressure which act on the tube when evacuated due to the presence of the bellows connection to the remainder of the vacuum system. With the target end of the tube bolted securely, the camera end is secured by simultaneously tightening two opposing lock nuts. These are hand-tightened only,
and are intended to prevent the tube from flexing when evacuated.

In order to test the success of these measures, and the validity of the assumption, a large micrometer was constructed of aluminum I-beams. This micrometer fits over the top of the magnet and measures the distance between points on two vertical exterior surfaces of the target holder and the camera. The micrometer was similarly supported to measure the distance between the same points when the tube was in place on the comparator. A standard bar was prepared to check the calibration of the micrometer and eliminate the possibility of deflections of its frame in handling. These measurements showed that differences of as much as .003 or .004 inches sometimes existed between the position clamped in the magnet and resting on the comparator. These figures are in agreement with the differences in 2R (measured before and after each experiment) which have shown an average difference of ±.007 cm for all the experiments conducted with the magnet in the past 15 months. The micrometer measurements also indicated that no detectable (i.e., greater than ±.001 inches) deflections occurred either when the tube was evacuated or when the field was turned on. Tests showed that the thermal expansion effects due to the current in the magnet and variations in room temperature were negligible with respect to possible deflections in handling.

On the basis of the above considerations, an error of ±.007 cm must be assigned to the distance 2R.
The Distance $X_0$

The distance from the light line to the particle group on the photographic plate is found from a plot of the distribution of particles determined by "reading" the plates under a microscope. This distribution is obtained by counting the number of particles in a sweep as a function of the distance, $X$, of the center of the sweep from the center of the light line. The width of the sweep is the apparent width between two parallel cross hairs of the microscope eye piece. This apparent width is approximately equal, for the magnification normally used, to the apparent width of the light line, in order that the position of the light line may be found by bracketing it between the cross hairs in a manner similar to that described for the measurement of $2R$. The height of the sweep is maintained constant by stops on the translation of the stage which limit the motion to the desired area. An additional cross hair is mounted in the eye piece perpendicular to the two parallel hairs. The particle tracks are then counted as they cross the single cross hair while moving between the two parallel cross hairs.

An analysis of the line shapes indicates that for a given group of particles the momentum corresponds to that of particles with a radius of curvature terminating at the detector with an $X_0$ given by the extrapolation of the straight leading edge of the distribution with the background level $X_0$. Thus the quantity $X_0$ is taken directly from a plot of the distribution with the distance $X$ as the ordinate and the number of tracks per sweep as the abscissa.
Such a graph, known as a plate data plot, is illustrated in Fig. 8.

With the assumption that errors of calibration of the translation scale of the microscope are negligible, the possibility of error in $X_o$ must lie in the determination of the positions of the light line and the end point of the particle group, and in the possibility that the measurement is made not along the focal diameter but along a line inclined at a small angle $\epsilon$ to the focal diameter.

The distribution of tracks is counted on a plate for the distance ($X_{max} = 15 \text{ mm}$), which lies within the central one inch of the gap considered to contain a sufficiently uniform field. The maximum error to be expected from misalignment of the plate is thus $X_{max} (1 - \cos \epsilon) \approx X_{max} \epsilon^2$, to a second order approximation. Since an effort is made to simulate on the microscope stage the conditions under which the plate is supported in the camera, the angle $\epsilon$ is not expected to exceed $2^\circ$. Under these conditions an error of not greater than $\pm 0.001 \text{ cm}$ in $X_o$ is to be expected from the plate alignment.

Since the light line on the photographic plate is more readily visible than that observed in the measurement of $2R$, an average deviation of $\pm 0.0003 \text{ cm}$ is observed in determining the position of the light line. However, the determination of the particle group end point is in general considerably less accurate. The errors of this assignment must usually be determined for each particular case, since they vary from one group to another due to the influence of such factors as the statistics of the data points, the condition of the target, and the background level.
Fig. 8 is a plot of a plate from one of the scandium spectra (Chapter VII). It shows three particle groups of different intensities, which are fairly representative of the range of intensities encountered. The probable errors in the assignment of $X_0$ are shown by bars at the intercept of each leading edge with the background. For the least intense group, with a peak value of 50 proton tracks per sweep, an assignment of ±0.018 cm is made for the error in $X_0$. More intense particle groups yield a smaller error, as shown in Fig. 8; and less intense groups may in some cases yield slightly larger errors. On the basis of these examples, it is estimated that the largest error which might appear in $X_0$ is about ±0.020 cm. However, most cases will probably show smaller error.

**Measurement of Frequency**

The procedure for the measurement of the frequency (and thus the strength of the magnetic field) at the position of the probe in the gap has been described in Chapter II. Since the probe must necessarily be inserted in an unused portion of the gap, explicit account must be taken of the fact that the fields, which the particles experience in traversing their orbits, differ from that at the measured position due to the slight non-uniformities of the field. The first order correction to the frequency set by means of the probe is made from a relation derived by Hartree\textsuperscript{6}. This relation is:

$$\Delta f_{\text{inh}} = \frac{1}{2} \int_0^\pi \Delta f(\phi) \sin \phi \ d\phi$$

(III-3)
In order to evaluate this correction, a "field probing" is conducted at the conclusion of each experiment with the annular magnet in the position it occupied during the experiment and with the $90^\circ$ analyzing magnet of the accelerator set at an average of the fields used in the experiment. The field probing is accomplished with the vacuum tube removed, by measuring the difference in frequency between the probe in the standard position and a similar probe which is moved around the gap. This difference is measured every $15^\circ$ through the full $180^\circ$ which the particles traverse in their orbits. That the measurement at $15^\circ$ intervals is sufficient is confirmed by the observed smooth nature of the variation $\Delta f$ between points. A sample plot of the inhomogeneity observed for a recent experiment is shown in the upper drawing in Fig. 9.

The numerical evaluation of the integral of Equation (III-3) is indicated by the shaded areas of this figure, where the observed $\Delta f$'s have been weighted by the $\sin \phi$ factor and straight lines drawn between the resultant points. Since in a normal spectrum the frequencies used cover a fairly wide region, it is necessary to measure the inhomogeneity correction at several frequencies over this region in order to determine the variation of the correction with frequency. The lower drawing of Fig. 9 shows the results of such measurements made for some of the experiments appearing in this report.

Although the setting of the magnetic field by means of the proton moment magnetometer is independent of hysteresis effects in the magnet, it was recently found that the observed inhomogeneities
Fig. 9

$\Delta f(\phi)$ vs $\phi$ DEGREES

$\Delta f_{\text{mm}}$ vs $f$ M.C./SEC.

$f = 33.0$ M.C./SEC.
of the field are definitely not independent. A maximum difference of 15 k.c./sec was found in the inhomogeneity corrections between the situations in which a given field of the magnet was approached from zero field and from a high field. This difficulty can be overcome in practice by recycling the magnet, when necessary, such that the field to be set is always approached from the same direction. Since spectra are generally obtained by decreasing the field for successive plates, it is convenient to raise the magnet current to produce a high field before the first frequency is set and to approach this setting from above. Under these conditions the inhomogeneity correction should be reproducible for any given frequency.

Since this recycling technique was not adopted until very recently, some uncertainty exists in the inhomogeneity corrections for the earlier data. However, the errors of the magnitude found in testing this effect are not expected to have occurred for this earlier data, since the field settings (except for the first setting of an experiment) were approached from above, and the field probings were conducted similarly. The excellent agreement of data obtained before and after the adoption of the proper technique bears out this conclusion.

Other than the question raised above concerning the inhomogeneity correction to earlier data, the chief sources of error are due to drifts in the oscillator frequencies and the current regulation system. As both of these effects are subject to visual monitoring with an oscilloscope, as described in
Chapter II, an upper limit of ±0.005 M.C./sec may conservatively be designated as the error in the frequency setting. Since the measurement of the inhomogeneity correction involves the same difficulties, an equal error of ±0.005 M.C./sec may be assigned for that measurement. Therefore, the resultant error in \( f_0 \), the corrected frequency from which the energy is calculated, should be on the order of ±0.007 M.C./sec.

**Measurement of the Angle \( \alpha \)**

The measurement of the angle \( \alpha \) is based upon the radius of curvature of the incident beam, \( \rho \), and the distances \( x \) and \( d \) indicated on part (c) of Fig. 7. The angle \( \alpha \) is related to these quantities by the relation

\[
\alpha = \frac{x}{2} - \arcsin \left( \frac{(x^2 + d^2)^{1/2}}{\rho} \right) - \arctan \left( \frac{d}{x} \right), \quad (III-4)
\]

which is derived from the geometry of the situation. The quantity \( x \) is related to the micrometer reading \( R_1 \) of part (c), Fig. 7, by the relation \( x = x_0 - R_1 \). The quantity \( x_0 \) is the distance, along the line of motion of the micrometer (parallel to the focal diameter) between the inboard edges of the traveling and target slits when the micrometer reads zero. The quantity \( d \) is the distance between the planes of the two slits, measured on a line perpendicular to the focal diameter.

Since equation (III-4) is relatively complex, its solutions are graphed in parametric form for practical use. Thus,
the angle $\alpha$ may be read directly from the graph in terms of $R_1$ and $\rho$. The quantity $\rho$ may readily be found since the energy of the incident beam and field of the magnet are known.

The errors in determination of $\alpha$ are no larger than $\pm 0.1^\circ$, since this error corresponds to $\pm 0.005$ inches in the micrometer reading. The chief uncertainty in $\alpha$ lies in the acceptance angle of the spectrometer which is $\pm 1.9^\circ$.
IV: ASSOCIATED TECHNIQUES

In addition to the primary measurements considered in Chapter III, a number of other techniques enter into experiments performed with the annular magnet. These fall largely into three categories: targets, photographic plates, and computations. A discussion of each of these aspects will be considered in this chapter. In addition, the problems associated with the use of the magnet with the accelerator will be considered, and a summary given of the errors of measurement with respect to the accuracy of the Q values.

Targets

The targets used for inelastic scattering experiments on the annular magnet must be thin with respect to energy loss of the particles in the beam. In this sense, thin means that protons of the energy range 3 to 5 Mev shall not lose more than about 25 kev in a single traversal of the material. In general, the targets used were less than 10 kev thick.

The targets used are generally layers of material evaporated onto thin supporting foils. In some cases sufficiently thin self-supporting foils are available of the material to be studied. For the evaporated targets supporting foils of several materials are available; these include nickel foils (electroplated onto copper backings by the Chromium Corporation of America), carbon foils (prepared by cracking methyl iodide vapor onto a heated
filament), and electroscope leaf foils of gold or aluminum. The nickel and carbon foils have been found to withstand beam action better than the electroscope leaf foils, and thus have been used most frequently with the magnet. The nickel foils require removal of the copper backing for use. This removal is accomplished by etching the copper away with a chromic acid solution after the foil is mounted on its target carrier.

Both the nickel and carbon foils exhibit difficulties, however, and it is frequently necessary to use both types for a single spectrum to assure complete coverage of the regions of interest. It has in most cases not been possible to obtain carbon foils as thin as desirable, and as a consequence a considerable region of a spectrum may be occupied by the elastic group from this nucleus. Although the elastic groups from nickel foils are not generally troublesome, two inelastic particle groups appear in the spectra. For higher bombarding energies these groups may be fairly strong. This question will be considered more fully in a later chapter in connection with the scandium spectra.

The question of contaminant materials in or on the targets presents a problem of considerable importance for inelastic scattering spectra. Although elastic groups resulting from such contaminants may usually be identified as such, as explained in Chapter I, they frequently lead to confusion, and, particularly for the stronger contaminants, the elastic groups may occupy significantly large portions of the spectra, making detection of inelastic groups from the target nuclei impossible in these areas. The
occurrence of the latter effect often necessitates bombardment at three or more energies to adequately inspect the desired region of excitation of the target nucleus.

The presence of carbon and oxygen as surface contaminants is not unexpected, as these elements usually appear in nuclear experiments in which a target is bombarded by particles from an accelerator. The presence of silicon and sulphur might also be expected, since it is known that both the quartz and zinc sulfide, utilized for viewing the beam, evaporate from the heat generated by the impingement of the beam. The presence of such elements as potassium, chlorine, aluminum, sodium, magnesium, and fluorine, which frequently appear in spectra, remains at present unexplained.

**Photographic Plates**

Nuclear track plates of both the Eastman Kodak NTA and the Ilford El types have been used with the magnet. These emulsions are similar in characteristics, both having been designed to register the paths of protons, deuterons, and alpha particles, without registering electrons or mesons. The Ilford plates have been found superior to the Eastman plates in that they do not exhibit the serious surface scratches which in some cases rendered the Eastman plates uncountable.

Since a grazing angle of 12.5° was used, it was possible to use emulsions 25 microns thick, thus permitting the use of simpler development techniques than required for the thick (greater than 100 micron) emulsions. The ordinary technique for the Ilford
emulsions consists of development for 15 minutes (20 minutes for supercoated emulsions) in D-19 (a fine-grain, high contrast developer), washing for 10 minutes in running water, and fixing for 25 minutes in a hardening fixer. The plates are then washed for one hour to assure permanence.

The design of the camera requires the use of 1 by 1.5 inch plates. Since nuclear plates are normally supplied in the standard 1 by 3 inch microscope slide size, a special jig has been constructed which permits cutting the plates in half at this laboratory.

The requirements for microscopes to read the plates differ from those of standard types only in the construction of the stage. The method of counting the tracks, described in Chapter III, requires two degrees of translational freedom: one direction with scales graduated to at least .001 cm, and an orthogonal direction in which motion is limited by stops to restrict it to the proper portion of the plate. The support of the plate must be designed to simulate the conditions of support in the camera, as was mentioned in Chapter III.

**Computations**

The discussion of this section is intended to describe the procedures used in obtaining Q values from the experimental measurements and to unify the concepts of the preceding chapters with respect to this end result. For convenience, a summary of the computational formulae are included in Table I.
\[ E_2' = A(m) \left( f_o \rho_o \right)^2 \]  \hspace{1cm} (1)

\[ A(m) = \frac{\pi^2 \gamma^2}{10^{-14} \gamma_p^2} \left( \frac{mp}{m} \right) \left( \frac{e}{mp} \right) \]  \hspace{1cm} (1a)

\[ f_o = f_{\text{set}} - f_{\text{inm}} \]  \hspace{1cm} (2)

\[ \rho_o = \frac{1}{2}(2R_o + X_o) \]  \hspace{1cm} (3)

\[ 2R_o = 2R + \Delta R_o \]  \hspace{1cm} (3a)

\[ E_2 = E_2' - \Delta E_{\text{rel}} - \Delta E_\alpha \]  \hspace{1cm} (4)

\[ \Delta E_{\text{rel}} = \frac{(E_2')^2}{2mc^2} \]  \hspace{1cm} (4a)

\[ \Delta E_\alpha = \frac{2E_2c^2}{1 + \frac{M+m}{m} \sqrt{\frac{E_2}{E_1}}} \]  \hspace{1cm} (4b)

\[ E_1 = \left( \frac{M-m}{M+m} \right)^2 E_2 \]  \hspace{1cm} (5)

\[ Q = \left( \frac{M+m}{M} \right) E_2 - \left( \frac{M-m}{M} \right) E_1 + \frac{2m}{M} \sqrt{E_1 E_2} \]  \hspace{1cm} (6)
TABLE II

**Fundamental Constants**

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_p$</td>
<td>$2.67522 \times 10^4 \text{sec}^{-1}\text{gauss}^{-1}$</td>
</tr>
<tr>
<td>$e/m_p$</td>
<td>$9.5734 \times 10^3 \text{emu} \cdot \text{gm}^{-1}$</td>
</tr>
</tbody>
</table>

* Summer, Thomas and Hipple, Phy. Rev. 82, 697 (1951)
Since certain of the computed quantities apply to all of the particle groups appearing on one plate, these quantities, $2R_0$, $f_0$, and $\alpha$, may be computed separately for each plate. Then for each observed group on a plate the $X_0$ may be combined with $2R_0$ for that plate to form $\rho_0$ (3). From $f_0$ and $\rho_0$ the uncorrected energy, $E_2'$ (1), may be obtained. $E_2'$ may then be corrected (4) by the relativistic (4a) and angular (4b) corrections. The elastic groups may be identified, and the bombarding energy, $E_1$, obtained from (5). Finally the $Q$ values of the inelastic groups may be obtained from (6).

In addition to the experimentally measured quantities, the masses of the particle and nuclei involved and certain fundamental constants enter into the computations. The masses used throughout have been those of Li et al$^7$ and for $A>20$, from Segrè$^8$. The values of the constants and their sources are listed in Table 2.

**Accelerator**

The Rice Institute 5.5 Mev Van de Graaff accelerator was used as the source of bombarding particles, in this case protons, for the experiments contained in this thesis.

The analyzing magnet used with the accelerator is equipped with two beam exit ports: one for $90^\circ$ deflection (mass one proton), and a second for $45^\circ$ deflection (mass two protons). In addition, adjustable shims at the emergence of each port from the magnet pole pieces allows independent adjustment of the shapes of the focus of both mass beams. It was thus possible to achieve an
essentially vertical focus for the mass one beam, to conform to the vertical slit system of the annular magnet, while simultaneously maintaining an essentially horizontal focus of the mass two beam, to produce maximum effectiveness of the accelerator voltage regulation at the horizontal slits of the mass two port.

As used with the annular magnet, the accelerator was adjusted to produce a total resolved mass one beam of one to three microamperes. The external slits, which defined the edge of the beam, cut off about one half of this current. Thus the focusing properties of the accelerator were sufficiently good that a beam of about one microampere ($6.25 \times 10^{12}$ protons per second) could be passed through an area .25 mm wide and 2.77 mm high at the target.

Two points concerning the beam provided by the accelerator are of primary importance to annular magnet experiments. These are the energy spread of the beam and the constancy of the beam energy with time. Experiments described in succeeding chapters indicate that the beam spread (for the region 3 to 5 Mev) is no greater than 3 kev and quite probably is less. The current regulation system of the analyzing magnet is of the same type as that of the annular magnet (described in Chapter II) with similar stable characteristics. Recently a proton-lithium moment magnetometer has been added to set and monitor the field of this magnet. It is thus to be expected that constancy of the field strength comparable to that of the annular magnet may now be obtained with the analyzing magnet. An average deviation of 1.7 kev has been observed for the bombarding energies calculated from elastically scattered groups in
several recently obtained spectra. As this value lies within the limits of accuracy to be expected from the experiments, it may be assumed the energy of the beam is constant to within the limits of the ability of the annular magnet to determine energy.

Errors of the Q Value

A summary of the estimates of error in the individual measurements and their influence on the calculated quantities are listed in Table III. The relative errors quoted are taken for a fictitious case of an observed proton group with an energy of $\frac{4}{4}$ Mev, and are intended only as an illustration of the relative magnitudes involved. For the errors in the Q listed, this fictitious proton group is assumed to correspond to a state of 1 Mev excitation in a nucleus of mass 40. The relative error listed for $E_1$ is based on the average deviation of the calculated values of $E_1$, reported in the preceding section.

It should be noted that the estimate of the error in Q, of Table III, assumes that each of the errors are completely random. This may not necessarily be the case. Errors arising from such sources as the deflection of the tube would, for instance, probably be constant throughout an entire spectrum, since such deflections are expected to occur only in handling.

For any error which remains essentially constant in magnitude and sign throughout a complete spectra, the error in the Q value will be in general less than that due to random errors of the same magnitude, since the Q value for inelastic scattering is


<table>
<thead>
<tr>
<th>Source</th>
<th>Probable Error</th>
<th>Relative Error (see text)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of Curvature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔR₀</td>
<td>± 0.004 cm</td>
<td></td>
</tr>
<tr>
<td>2R</td>
<td>± 0.007 cm</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>± 0.020 cm</td>
<td></td>
</tr>
<tr>
<td>ρ₀</td>
<td>± 0.011 cm</td>
<td>3.1 \times 10^{-4}</td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fₛₑₑ</td>
<td>± 0.005 M.C./sec</td>
<td></td>
</tr>
<tr>
<td>fᵢᵣᵢᵢ</td>
<td>± 0.005 M.C./sec</td>
<td></td>
</tr>
<tr>
<td>f₀</td>
<td>± 0.007 M.C./sec</td>
<td>2.0 \times 10^{-4}</td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E₂</td>
<td>± 0.0030 Mev</td>
<td>7.4 \times 10^{-4}</td>
</tr>
<tr>
<td>ΔEᵣₑₑ</td>
<td>± 0.0001 Mev</td>
<td></td>
</tr>
<tr>
<td>ΔEᵣᵢᵢ</td>
<td>± 0.0010 Mev</td>
<td></td>
</tr>
<tr>
<td>E₂</td>
<td>± 0.0032 Mev</td>
<td></td>
</tr>
<tr>
<td>Q Value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E₁</td>
<td>± 0.0017 Mev</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>± 0.0039 Mev</td>
<td></td>
</tr>
</tbody>
</table>
essentially the difference in the energies $E_1$ and $E_2$ (Equation 6, Table I), and a systematic (constant) error will have the same relative effect on both energies. In fact, it may be shown that the relative error in the Q value due to a systematic error is nearly equal to the relative error in the energy measurements. Thus, particularly for low Q values, this error in the Q value will be quite small.

Since the extent to which an error analysis, such as that of Table III, contains constant factors is highly indeterminate, the results of such an analysis should be considered an upper limit on the error of the Q. No attempt will be made to separate random errors from systematic errors. Instead, for the lower Q values, where small systematic errors are of negligible effect, the internal consistency of the data should provide a reasonable estimate of the random errors, provided that a sufficient number of observations are available to make such an analysis meaningful. For the higher Q values some account of the systematic errors must be taken, and the values of the error assignments will approach those of the error analysis.

The question of energy loss of the incident and observed particles in the contaminant layers on the target must be considered in any precision experiment. Fortunately, this factor may be shown to be negligible in most cases for proton inelastic scattering at the energies considered in this thesis. An experiment which will be considered in a later chapter indicates that the amount of material deposited in the contaminant layers produces energy losses
of less than 1 kev for all but the lowest energy protons considered, provided that targets are used which have not received excessive bombardments. Since the dE/dR curve for protons is relatively flat in this region of energies, the effect of the contaminant layers will be essentially the same on both $E_2$ and $E_1$. Thus, such errors may be considered systematic for all but the cases involving very low energy protons, and as such will produce negligible effects for $Q$ values up to about 1.5 Mev.
V: THE $^{19}_\text{F}(p,p')^{19}_\text{F}$ EXPERIMENT

Chronologically, the first inelastic scattering experiment attempted with the annular magnet was the analysis of the inelastic scattering of protons from fluorine. At the time these experiments were begun, there was considerable interest in the number and spacing of the low-lying levels of this nucleus, which were first reported by Mileikowski and Whaling\textsuperscript{9} from a study of the $\text{Ne}^{21}(d,\alpha)^{19}_\text{F}$ reaction. Since most of the techniques and some of the apparatus were developed during the time the experiments were being conducted, the experiments covered a span of almost a year. The report of this work\textsuperscript{10} has been accepted for publication in the Physical Review.

Spectra of this reaction were taken at a total of six bombarding energies from 2.153 to 4.533 Mev. Four of these spectra are shown in Figures 11-14. Fig. 10 contains a plot of $E_2$ vs. $E_1$ at $\theta = 180^\circ$ for the fluorine scattering. The solid lines represent the three fluorine groups while the elastic group from the carbon and oxygen contaminant are dashed. The fluorine lines and the contaminant lines do not differ greatly in slope because of the proximity of the mass numbers (see Equation I-5) of the nuclei involved. Since the carbon and oxygen give the characteristic double particle group corresponding to contaminant layers from both the front and back surfaces of the foil, they obscure a significant part of each spectra. It was thus necessary to utilize a wide range of bombarding energies in order to adequately investigate
Fig. 14

[Graph showing energy and number of protons with specific annotations: $^{12}C$, $^{16}O$, $^{19}F$, $^{14}N$, and $^{20}Ne$.]
### TABLE IV

**Summary of the Experimental Results**

<table>
<thead>
<tr>
<th>Bombarding Energy Mev</th>
<th>Half-Width F19 Groups kev</th>
<th>% Intensity of Ground State Detectable***</th>
<th>Range of Excitation kev</th>
<th>First Excited State Q Value kev</th>
<th>% Intensity of Ground State</th>
<th>Second Excited State Q Value kev</th>
<th>% Intensity of Ground State</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1534</td>
<td>13</td>
<td>2</td>
<td>440</td>
<td>109.7</td>
<td>2</td>
<td>198.7</td>
<td>6</td>
</tr>
<tr>
<td>2.8394</td>
<td>11</td>
<td>3</td>
<td>440</td>
<td>*</td>
<td>*</td>
<td>198.3</td>
<td>62</td>
</tr>
<tr>
<td>2.9566</td>
<td>11</td>
<td>**</td>
<td>360</td>
<td>110.0</td>
<td>**</td>
<td>195.7</td>
<td>**</td>
</tr>
<tr>
<td>3.1818</td>
<td>12</td>
<td>4</td>
<td>425</td>
<td>111.4</td>
<td>12</td>
<td>198.3</td>
<td>17</td>
</tr>
<tr>
<td>4.1398</td>
<td>6</td>
<td>7</td>
<td>680</td>
<td>110.9</td>
<td>14</td>
<td>198.9</td>
<td>43</td>
</tr>
<tr>
<td>4.5320</td>
<td>52</td>
<td>8</td>
<td>730</td>
<td>110.1</td>
<td>17</td>
<td>196.6</td>
<td>144</td>
</tr>
</tbody>
</table>

* Covered by $^0_{16}$ ground state group

** Spectra did not include ground state

*** Criterion for detectability: three times counting statistics of background
TABLE V

Comparison of Reported Q Values

<table>
<thead>
<tr>
<th>Source</th>
<th>Experiment</th>
<th>First Excited State kev</th>
<th>Second Excited State kev</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$^{19}F(p,p')*^{19}F$ mag. spec.</td>
<td>108.8 ± 0.8</td>
<td>196.0 ± 1.4</td>
</tr>
<tr>
<td>B</td>
<td>$^{19}F(\alpha,\alpha')*^{19}F$ gamma ray</td>
<td>113 ± 2</td>
<td>196 ± 2</td>
</tr>
<tr>
<td>C</td>
<td>$^{19}F(p,p')*^{19}F$ mag. spec.</td>
<td>110.4 ± 0.6</td>
<td>197.8 ± 1.2</td>
</tr>
</tbody>
</table>

A: Peterson, Fowler and Lauritsen, Phy. Rev. 96,1250 (1954)


C: Present report.
this region of excitation in fluorine.

The results of six determinations are listed in Table IV. Also tabulated is information bearing on the possibility of the existence of other states of F\textsuperscript{19}. Upper limits may be set for the intensity of any possible undetected groups resolvable from the known groups, using the criterion that a group of intensities three times the counting statistics of background would be detectable. The half-width of the fluorine groups and the range of excitation energy of F\textsuperscript{19} covered by each spectra are also listed.

Table V contains a comparison of these Q values with other recent determinations. The errors quoted for the present results are based solely on internal consistency. The estimation of an upper limit for the error in the energy assignment for an individual group, based on a systematic analysis of the possible sources of error, such as that of Chapter IV, is of the order of 4 kev; however, small systematic errors constant throughout a spectrum make negligible contributions to the error of the Q value, since these Q values are less than 200 kev. Thus, only the random errors contribute significantly, and the internal consistency should provide an adequate representation of the errors.

On the basis of spectra obtained for cases where two known groups were superimposed but not resolved, it is estimated that if doublet structure, with a separation of 3 kev or more, existed it would have been possible to detect its presence, provided that one group had an intensity of at least 25 percent of the other. From the data of Table IV it may be seen that groups of 6 kev or more
separation could have been resolved. It may also be seen that any isolated group with an intensity of approximately 2 percent of the ground state fluorine group would have been detected; and furthermore, with the range of bombarding energies used, there exist no gaps in the excitation of F isotope in which a state could be hidden by a contaminant group.
VI: The $^{9}\text{Be}(p,p')^{9}\text{Be}$ and $^{9}\text{Be}(p,\text{pn})^{8}\text{Be}$ Reactions

For some time the 2.43 Mev state of $^{9}\text{Be}$ has been believed to be the first excited state in this nucleus. However, recently other groups\textsuperscript{11,12} have reported the possible existence of a state at about 1.6 to 1.8 Mev. In order to investigate this region with an instrument of greater precision than that which was available to these other experimenters, the Rice Institute annular magnet was used to obtain a spectrum of the protons observed from proton bombardment of this nucleus. The region of excitation from the ground state through the 2.43 level was examined.

Fig. 15 is a plot of the proton spectrum obtained. The region of excitation from the ground state to about 1.4 Mev has been omitted from the plot as the background in this region showed no structure. In addition to the ground state and 2.43 Mev state groups, a broad distribution of protons appears which, if considered to be a state in $^{9}\text{Be}$ observed by the inelastic scattering mechanism, will have a $Q$ of 1.675 Mev. In order to establish that this proton group is associated with the $^{9}\text{Be}$ nucleus, the group was observed at three different bombarding energies. The results of these experiments are shown in Fig. 16, where an abscissa showing excitation in $^{9}\text{Be}$ has been provided, and also in Table VI, which lists the computed $Q$ values. The agreement of these values of the $Q$ establishes, as explained in Chapter I, that this group is associated with $^{9}\text{Be}$.

There are at least four possible mechanisms which may
Fig. 16

$Q$ MEV

$Be^9(P,PN)$
$E_1 = 4.800$

NUMBER OF PROTONS

$Be^9(P,PN)$
$E_1 = 5.031$

B$\rho$ KILOGAUSS-CM.

$Be^9(P,PN)$
$E_1 = 5.242$
TABLE VI

Summary of Observed Q Values for the 3 Body Disintegration

<table>
<thead>
<tr>
<th>Bombarding Energy MeV</th>
<th>Q Value MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7996</td>
<td>1.6752</td>
</tr>
<tr>
<td>5.0308</td>
<td>1.6768</td>
</tr>
<tr>
<td>5.2423</td>
<td>1.6712</td>
</tr>
<tr>
<td>5.2445</td>
<td>1.6758</td>
</tr>
<tr>
<td>5.2537</td>
<td>1.6776</td>
</tr>
</tbody>
</table>

Mean: 1.675 ± 0.002
be used to explain the existence of this group. These are: (1) inelastic scattering, wherein the compound nucleus, \( B^{10} \), emits a proton leaving the residual nucleus, \( Be^{9} \), in an excited state; (2) two successive discrete emissions, wherein the compound nucleus emits a neutron of discrete energy leaving the \( B^{9} \) nucleus either in the ground state or in an excited state; this nucleus, being unstable to proton emission, then emits a proton of discrete energy, leaving the residual nucleus \( Be^{8} \); (3) the three body break-up, wherein a neutron and proton are emitted simultaneously, leaving the residual nucleus, \( Be^{6} \); and (4) the four body break-up, wherein the neutron, proton and two alpha particles separate simultaneously. At the bombarding energies used in this experiment, all of these processes are energetically possible.

Two types of evidence from the annular magnet experiment favor the three body mechanism to exclusion of the others. The first of these is the observed asymmetry in the particle distribution, shown in Fig. 15. Certainly no asymmetry is to be expected in the distribution of energies of particles emitted by a nucleus excited to a single isolated nuclear state, of whatever width. Furthermore, it is considered highly unlikely that any instrumental factors could produce this degree of asymmetry from an initially symmetrical group of particles. The essentially symmetrical distribution from the ground and 2.43 states are offered in support of this point of view. The slight asymmetries which are apparent for these groups are attributed to straggling in the target foil. Such straggling would not affect a broad group of particles from the same foil any
more strongly than it affects the narrow groups.

It is therefore concluded that the observed distribution cannot be attributed to inelastic scattering from a single state. However, the evidence does not exclude the possibility of the existence of two or more states, which could conceivably overlap to produce the observed distribution. Such a hypothesis is probably unlikely if a simpler mechanism may be found to explain the distribution. Furthermore, due to the statistics and the necessity of normalization (see below), the possibility cannot be excluded that a weak group due to a single state of Be\(^9\) might not be observed in the presence of a group produced by another mechanism.

The normalization, mentioned above, has been made for the plot of Fig. 15. The necessity for this normalization arises from the fact that the background, while statistically constant for a given plate may differ from plate to plate. Such fluctuations may be expected from the alignment procedure discussed in Chapter III. Although this procedure is designed to minimize the background, it does not assure the same background level for different settings. The normalization procedure was achieved in the following manner: the average background level was found for all of the plates which showed statistically flat backgrounds, and the observed backgrounds were corrected to this average value. The plates, upon which the broad state is shown, all appear to demonstrate a distinct non-zero slope for the distribution of tracks across the plate. The background correction for these plates was determined by matching each plate to the neighboring plates to give a smooth distribution. The
points at which the normalizations occurred are indicated by arrows in Fig. 15.

Although the mechanism of two successive discrete emissions might under some circumstances produce such a broad asymmetric distribution, it can be shown that for such a mechanism to produce protons of the energy observed, a state below 1 Mev in excitation of the B\textsuperscript{9} nucleus must be hypothesized. A study of the Be\textsuperscript{9}(p,n)*B\textsuperscript{9} reaction made by Marion\textsuperscript{13} shows no evidence for the existence of such a state. It is thus concluded that this is also unlikely.

The work of Ajzenberg and Buechner\textsuperscript{14} on the Be\textsuperscript{9}(p,n)*B\textsuperscript{9} reaction showed a continuous distribution of neutrons which rises toward lower neutron energies. They attribute these neutrons to the three body disintegration. The hypothesis of such a three body process also appears to be supported by the annular magnet data. The exact momentum distribution of the protons to be expected from such a process has not been worked out. However, from considerations of the available volumes in phase space, it appears likely that a distribution peaked toward higher momenta for the proton may be expected. Certainly the proton penetrability is not sufficient to explain the fairly rapid drop-off observed, although it will remove any very low energy protons.

The proximity of the Q value observed with the annular magnet to the value of the energy release in the three body break-up is also suggestive that the observed group is due to such a process. It may be shown that the maximum energy proton for the three body
disintegration corresponds to zero relative velocity between the neutron and Be$^8$ nucleus. In this respect a Q value calculation, in the manner described in Chapter III, is valid for the maximum energy protons. However, the assignment of $X_0$ from the extrapolated leading edge of the distribution is not valid in that it ignores the neutron penetrability. A consideration of this factor would lower the energy of the maximum energy protons observed, since protons with energy near the maximum correspond to very low relative separation velocities of the neutron and Be$^8$ nucleus. As this relative velocity approaches zero the penetrability of the neutron rapidly approaches zero, and consequently the probability for the three body decay becomes vanishingly small.

In this sense the high energy edge of the proton distribution is similar to a threshold for neutron emission, and as such should show the characteristic $E^{1/2}$ dependence, generally observed for $\lambda = 0$ neutrons. Unfortunately, the statistical errors for the leading edge of the observed distribution are not sufficiently accurate to permit other than a linear fit.

Such a penetrability argument is probably the explanation for the discrepancy between the Q value observed by the annular magnet, $1.675 \pm .002$ Mev, and that observed by Mobley and Laubenstein$^{15}$ who obtained a Q value of $1.666 \pm .002$ Mev for the $\gamma,n$ threshold.

The Q value obtained with the annular magnet probably excludes the possibility of the four body disintegration, since the additional 96 kev provided by the break-up of Be$^8$ into two alpha
particles would cause the expected Q value of the disintegration to differ widely from the observed value.

The evidence, which has been published for the existence of a state in Be$^9$ in the vicinity of the group observed with the annular magnet, has been based upon the decay of the compound nuclei $B^{10}$ and $C^{13}$, which were assumed to decay as $B^{10} \rightarrow p + Be^9$ and $C^{13} \rightarrow \alpha + Be^9$, respectively. A possibility may exist that the groups observed were due to the three body decay scheme: $B^{10} \rightarrow p + n + Be^8$, and $C^{13} \rightarrow \alpha + n + Be^8$. It may be shown that in these three body disintegrations the Q value observed from the maximum energy charged particle should correspond to the energy release in the $Be^9 + n$ break-up. However, as stated above, the evidence of the annular magnet experiment, while probably establishing that protons from the three body disintegration do occur, does not conclusively exclude the possibility of the existence of a state in Be$^9$.

A study of the known 2.43 Mev state of Be$^9$ was conducted in conjunction with the study of the three body disintegration. A summary of the Q values obtained is included in Table VII. On the basis of internal consistency, a probable error of $\pm 0.001$ Mev could be assigned for the average value of the five observations. However, since this state corresponds to a relatively high Q, the possibility of systematic errors affecting the observed value cannot be neglected. Therefore, on the basis of the analysis of Chapter IV, an error of $\pm 0.004$ Mev is assigned. A comparison with other values reported for this state is contained in Table VIII.
<table>
<thead>
<tr>
<th>Bombarding Energy (Mev)</th>
<th>Q Value (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6117</td>
<td>2.4321</td>
</tr>
<tr>
<td>5.2434</td>
<td>2.4325</td>
</tr>
<tr>
<td>5.2434</td>
<td>2.4276</td>
</tr>
<tr>
<td>5.2445</td>
<td>2.4321</td>
</tr>
<tr>
<td>5.2537</td>
<td>2.4354</td>
</tr>
</tbody>
</table>

Mean: 2.432 ± .004


### TABLE VIII

Comparison of Observed Q Values with Other Determinations

<table>
<thead>
<tr>
<th>Source</th>
<th>Experiment</th>
<th>Reported Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Be$^9(p,p')$*Be$^9$ mag. spec.</td>
<td>2.432 ± .004</td>
</tr>
<tr>
<td>B</td>
<td>Be$^9(p,p')$*Be$^9$ elec. spec.</td>
<td>2.433 ± .005</td>
</tr>
<tr>
<td>C</td>
<td>B$^{11}(d,\alpha)$*Be$^9$ mag. spec.</td>
<td>2.422 ± .005</td>
</tr>
<tr>
<td>D</td>
<td>B$^{11}(d,\alpha)$Be$^9$ mag. spec. *</td>
<td>2.431 ± .006</td>
</tr>
</tbody>
</table>

A: Present work

B: Browne, Williamson, Craig and Donahue. Phy. Rev. 83,179 (1951)

C: Van Patter, Sperduto, Huang, Strait, and Buechner, Phy. Rev. 81,233 (1951)

Since the observed protons of the group corresponding
to this state had energies of about 1.05 and 1.45 Mev for the 4.61
and 5.25 Mev bombardments, respectively, it was necessary to consider
the possible energy losses in the contaminant layers of the foil.
Fortunately, in this case a means of evaluating this loss was
available. The alpha particle group from the Be⁹(p,α)*Li⁶ group,
leaving Li⁶ in the 2.187 state, appeared in the momentum region
near the proton group from the 2.43 state of Be⁹. Since the energy
loss of the alpha particles in the contaminant layer was a factor
of 8 greater than that of the protons for the energies observed, it
was possible to obtain a fairly sensitive estimate of the thickness
of the contaminant layer from the difference between the observed
Q value for the alpha group and the Q observed by Browne et al.¹⁶
The losses of the protons were then computed for this thickness
and the Q values corrected accordingly. It was found that corrections
of less than 1 kev were required for protons in cases where fairly
fresh foils were used. In one extreme case, where the foil had
been bombarded a number of times previously and showed quite heavy
carbon markings, a correction of only 3 kev was indicated.

The observed increased width (shown in Fig. 15) of the
proton group from the 2.43 Mev state, as compared to the width of
the proton group from the ground state, was that to be expected
from the additional energy loss of the lower energy protons in the
foil. Since this method did not provide a very adequate means of
determining the natural width of the state, a more sensitive method
was devised. For this experiment a very thin beryllium target was
evaporated onto a carbon foil. The proton group for the 2.43 state was then observed with a bombarding energy of 5.25 Mev, and the ground state group observed at a bombarding energy of 3.00 Mev, computed to give the protons the same energy loss in the physical thickness of the target. The results of this experiment are shown in Fig. 17. Both groups show a thickness at half maximum of 3.2 kev.

To evaluate the results of this experiment a consideration must be made of the factors which contribute to the observed width of a group. These factors include: the natural width of the state; the physical thickness of the target material with regard to the energy loss of the particle; the geometrical width of the beam of bombarding particles at the target; the energy spread of the particles of this beam; and the spectrometer width, which will be a combination of such effects as the acceptance angle of the spectrometer, second order focusing effects, and the effect of inhomogeneities of the field.

It was possible for this experiment to adjust most of the controllable factors to produce approximately equal effects on the widths of the observed groups. After subtraction of the calculable quantities of geometrical beam width and energy loss in the target, there remains the natural width of the state, the beam spread and the spectrometer width. If the spectrometer width is considered to be entirely due to the spectrometer acceptance angle of \( \pm 1.9^\circ \), then calculation shows that the half-width of the inelastic proton group and the elastic proton group should be 5.1 and 2.5 kev, respectively. The reason is not understood for the
appearance of the inelastic group with less width than the calculated value. However, the fact that the observed width is smaller than that calculated indicates that the state must have a very narrow natural width.

An increase in the spread of the beam energy at the lower bombarding energy could produce an effect which would give the observed group from the ground state the same width as that observed for the group from the 2.42 state, which might contain contributions from a natural width of the state. However, such an increase in the spread at lower energies would be contrary to experience, which has shown such energy spreads to be relative and thus smaller at lower bombarding energies. On this assumption, it would appear that the state has no detectable natural width. An upper limit of 1 kev may be set for the natural width of the state to take into account such factors as are not understood.

Since the 2.43 state of Be⁹ is about 766 kev unbound to neutron emission, an appreciable width would be expected for this state, if low ℓ neutron emission were possible. The fact that a narrow width is observed for the proton group implies that a high centrifugal barrier exists for the neutrons. Calculations indicate that a lower limit of J = 5/2 may be set for this state on this basis.

An estimate may be made of the cross sections for the proton groups of Fig. 15. The values and the angle at which they were observed are listed in Table IX. These values should be accurate to approximately ± 30%, except in the case of the three
<table>
<thead>
<tr>
<th>Particle Group</th>
<th>$\sigma$ \text{ m.b./steradian}</th>
<th>$\theta$ \text{ degrees}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground State</td>
<td>23 $\pm$ 10</td>
<td>174.2 $\pm$ 1.9</td>
</tr>
<tr>
<td>Three Body</td>
<td>1.2</td>
<td>172.3 $\pm$ 1.9</td>
</tr>
<tr>
<td>2.43 MeV State</td>
<td>3.6 $\pm$ 1.1</td>
<td>170.7 $\pm$ 1.9</td>
</tr>
</tbody>
</table>
body disintegration, where the cross section is somewhat indeterminate from our data. The target thickness found from the energy loss for the protons for the 2.43 state was 75μgm/cm². The value of the solid angle of the spectrometer was taken as (1.0 ± .2) x 10⁻⁴ steradians.
VII: The $^{45}\text{Sc}(p,p')^{45}\text{Sc}$ Experiment

The inelastic scattering of protons from the nucleus $^{45}\text{Sc}$ is of interest because it is the only method presently available for observing the level structure of this nucleus by precision magnetic analysis. Since $^{45}\text{Sc}$ is the only stable isotope of scandium, the $d,p$ reaction, which has been used to study some of the elements in this region, is not possible. The $d,\alpha$ reaction from the abundant isotope of titanium has a negative $Q$ of about 1.5 Mev, calculated from the available masses*. Thus, due to the height of the coulomb barrier for alpha particles for a nucleus of this high $A$, rather high deuteron bombarding energies would be required to obtain sufficient numbers of alpha particles for a precision analysis.

The $\beta^-$ decay of $^{45}\text{Ca}$ produces no information of the level structure of $^{45}\text{Sc}$, since this beta has an observed maximum energy of .250 Mev\textsuperscript{17}. The $\beta^+$ decay of $^{45}\text{Ti}$ has a maximum energy of 1.02 Mev; however, various observers\textsuperscript{18,19,20} have not been able to agree on the presence of gamma rays from this reaction. The only reported value\textsuperscript{19} of .450 Mev does not agree with any level found by the annular magnet analysis.

A recent search for low-lying levels of nuclei in this region, performed by Temmer and Heydenberg\textsuperscript{21} indicated a level in $^{45}\text{Sc}$ at 388 kev. Since this work was concerned with levels below 500 kev, it is not surprising that no report was made of the 541 kev state, which is the next highest level observed in the annular
magnet experiments. The disagreement of 11 kev shown between
the scintillation measurements and the magnetic analysis value is
not usual in view of the relatively less accurate scintillation
measurements.

Due to the complexity of the inelastic proton spectrum
observed in the initial bombardment of the nucleus at $E_1 = 5.61$ Mev,
additional spectra were obtained at two lower bombarding energies,
$E_1 = 4.5$ and $E_1 = 5.0$ Mev. These energies were chosen such that any
groups, obscured by elastic groups from contaminants at one bomb-
arding energy, would be observable at the other two bombarding
energies, in order to provide the two observations necessary to
determine with which nucleus a group is associated. The three
spectra obtained in this manner are illustrated in Figs. 18-20.
The assignments for each proton group are indicated on the drawings.
The observed Q values for each level, ascribed to Sc$^{45}$, are listed
in Table X with bombarding energy at which they were observed.

In order to assist in evaluating the evidence for the
observed levels, a "Q-plot" is shown in Fig. 21. This plot indicates
the equivalent Q value of each of the observed proton groups as a
function of the bombarding energy at which they were observed.
On such a plot groups which are due to the same state in Sc$^{45}$ will
have the same Q value, and will appear to define a line of slope
zero (shown as a solid line) in Fig. 21. Groups which are due to
elastic or inelastic scattering from nuclei of other masses, i.e.,
contaminants or target backing material, will define lines of non-
zero slope (shown dashed in Fig. 21). It should be pointed out that
<table>
<thead>
<tr>
<th>Bombarding Energy: (MeV)</th>
<th>4.5142</th>
<th>5.0326</th>
<th>5.6080</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Q Value: (MeV)</td>
<td>.3757</td>
<td>.3765</td>
<td>.3777</td>
<td>.377 ± .002</td>
</tr>
<tr>
<td></td>
<td>.5400</td>
<td>.5413</td>
<td>.5406</td>
<td>.541 ± .002</td>
</tr>
<tr>
<td></td>
<td>.7195</td>
<td>*</td>
<td>.7244</td>
<td>.722 ± .005</td>
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<td></td>
<td>.9724</td>
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<td>1.2378</td>
<td>1.2330</td>
<td>1.2327</td>
<td>1.235 ± .005</td>
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<tr>
<td></td>
<td>1.2350</td>
<td>1.2330</td>
<td>1.2327</td>
<td>1.235 ± .005</td>
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<tr>
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<td>1.4088</td>
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<tr>
<td></td>
<td>1.4323</td>
<td>1.4292</td>
<td>1.4308</td>
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<tr>
<td></td>
<td>1.6622</td>
<td>1.6596</td>
<td>1.6605</td>
<td>1.661 ± .004</td>
</tr>
</tbody>
</table>

* Proton group obscured by elastic group from 0^16.
the actual assignments of levels are made from the agreement of the
calculated Q values, and not from Fig. 21, which is included only
to help visualize the situation.

The contaminants potassium, chlorine, and sulfur appear
weakly in some of the spectra. These groups are identifiable as
such in each case and no evidence for Sc\textsuperscript{45} levels is found in this
region. The elastic group from silicon appears strongly in each
spectra. Groups calculated to be due to sodium and magnesium are
observed in the 4.5 Mev and 5.0 Mev spectra, respectively. The
source of such different contaminants in different spectra is not
understood. However, the Q values calculated from groups which
appeared on the same plates show good agreement and indicate the
existence of a scandium level at 377 kev, which is believed to be
the first excited state of this nucleus. The next observed level
at 541 kev also appears well-established due to the agreement of the
Q value and the lack of contaminant groups in this region. A level
of 722 kev also appears well-established. Although the group
corresponding to this level does not appear in the 5.0 Mev spectrum,
since the appropriate region is occupied by the elastic group from
oxygen; the observed groups at the other bombarding energies do not
correspond to elastic groups for any known elements.

A level of Sc\textsuperscript{45} may possibly exist at about 860 kev. A
group from this level would not appear in the 5.6 Mev spectrum,
as it would lie in the region occupied by the elastic group from
oxygen. Since the Q values of 856 kev and 865 kev calculated for
the groups from the 4.5 Mev and 5.0 Mev spectra, respectively, do
not agree within the limits observed for the other levels of scandium and since these groups give good agreement if they are assumed to be due to elastic scattering from the nuclei $^{13}C$ and $^{14}N$, respectively, it is concluded that no such level exists for scandium.

However, the existence of $^{13}C$ and $^{14}N$ as contaminants for the scandium targets is not well-established. The group which could be attributed to nitrogen in the 5.6 Mev spectra is believed to be at least partially due to the 972 kev level in scandium. This level is well-established by its appearance in the other two spectra. The elastic group from nitrogen in the 5.0 Mev spectra may possibly correspond to a 860 kev state in scandium as noted above. An elastic group from nitrogen would not be expected to appear in the 4.5 Mev spectra, as this region is obscured by the presence of the elastic group from the oxygen from the back of the foil.

The group ascribed to $^{13}C$ in the 5.6 Mev spectra may possibly correspond to a level in $^{45}Sc$ at 1.064 Mev. Groups corresponding to such a level in scandium would not be expected to appear in the other spectra due to the presence of the elastic groups from $^{12}C$. There is possibly some evidence for the appearance of $^{13}C$ in the 5.0 spectrum. The group ascribed to $^{13}C$ in the 4.5 spectrum may be due to an 860 kev state in $^{45}Sc$, as noted above.

The existence of levels in scandium at 1.235 Mev, 1.409 Mev, and 1.432 Mev appears well-established by the observation of groups in at least two of the three spectra in each case. Some difficulty is experienced in these regions of the spectra due to
the presence of groups\textsuperscript{22} from the 1.453 Mev state in Ni\textsuperscript{58} and the 1.329 Mev state in Ni\textsuperscript{60}. Both of these groups appear strongly in all three spectra since nickel foils were used as the target backing material. Difficulty was experienced with these groups particularly in the 4.5 Mev and 5.0 Mev spectra where the nickel foils appeared to be unaccountably thick. For this reason these regions of the spectra were investigated again by bombarding, at the same energies, scandium targets evaporated onto carbon foil backings. The resultant portions of the spectra are also shown in the spectra of Figs. 19 and 20. The structure observed in the distributions attributed to the excited states of nickel is believed to be due to levels in the compound nuclei, Cu\textsuperscript{59} and Cu\textsuperscript{61}. Excitation curves for the reaction Ni\textsuperscript{58}(p,γ)Cu\textsuperscript{59} have very recently been obtained at this laboratory\textsuperscript{23}. This excitation function shows a structure similar to that observed. No effort has been made as yet to compare these results.

The presence of groups, ascribable to B\textsuperscript{11} and B\textsuperscript{10}, observed in the 5.6 Mev spectrum, has not been explained. An elastic group from B\textsuperscript{11} would not be expected to appear in the other spectra due to the presence of elastic groups from C\textsuperscript{12} on the back of the foils. Elastic groups from B\textsuperscript{10}, however, should be observable on both spectra, but no evidence for such groups is found. The fact that no groups corresponding to such a Q value in Sc\textsuperscript{45} are found indicates that the groups ascribed to the boron isotopes in the 5.6 Mev spectrum, are probably not due to levels in scandium.
Weak groups appear on all three spectra which indicate a level in scandium at 1.651 Mev. A group was also observed in the 5.0 Mev spectra corresponding to a Q of 1.533 Mev in Sc$^{45}$. However, since no evidence for such a level in scandium was found in the other two spectra, no assignment of a state is made for this group.

From the usual scheme of nuclear energy levels, it is to be expected that a large number of discrete levels, undetected in these experiments, exists in the region of excitation of scandium above 1.4 Mev. However, as proton groups corresponding to such levels will have relatively low energies at the bombarding energies used, it is to be expected that their penetration of the coulomb barrier is sufficiently low that these groups would not be detectable in these experiments. For this reason, the weak groups of excitation of about 2 Mev found in the 5.6 Mev spectrum have not been attributed to scandium.

Rough estimates of cross section are given in Table XII. As the cross section measurement was not the primary purpose of the experiments, the targets used were not weighed. An estimate of the target thickness was made in each case from the observed widths of the particle groups. Since the width due to energy loss of the protons in the target material may have been less than the width due to other factors in some cases, the quoted cross sections are probably not good to better than a factor of two. As such, they are intended only as a guide to other workers who may wish to
**TABLE XI**

**Observed Cross Sections for the Sc$_{45}$(p,p')*Sc$_{45}$ Reaction**

<table>
<thead>
<tr>
<th>Bombarding Energy</th>
<th>E$_1$ = 4.514</th>
<th>E$_1$ = 5.033</th>
<th>E$_1$ = 5.608</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q Mev</td>
<td>$\sigma$ m.b./ster.</td>
<td>$\sigma$ m.b./ster.</td>
<td>$\sigma$ m.b./ster.</td>
</tr>
<tr>
<td>.377</td>
<td>.17</td>
<td>.22</td>
<td>.30</td>
</tr>
<tr>
<td>.541</td>
<td>.24</td>
<td>.45</td>
<td>.26</td>
</tr>
<tr>
<td>.722</td>
<td>.24</td>
<td>*</td>
<td>.30</td>
</tr>
<tr>
<td>.972</td>
<td>.19</td>
<td>.39</td>
<td>.36**</td>
</tr>
<tr>
<td>1.235</td>
<td>.18</td>
<td>.42</td>
<td>*</td>
</tr>
<tr>
<td>1.409</td>
<td>*</td>
<td>.25</td>
<td>.16</td>
</tr>
<tr>
<td>1.432</td>
<td>*</td>
<td>.28</td>
<td>.14</td>
</tr>
<tr>
<td>1.661</td>
<td>.12</td>
<td>.19</td>
<td>.12</td>
</tr>
</tbody>
</table>

* Coincident with stronger elastic group

** Coincident with weaker elastic group
investigate the matter more thoroughly.

An energy level diagram is shown in Fig. 22 of the states observed in this experiment to be ascribable to Sc$^{45}$. The level diagrams of neighboring nuclei are not shown, since the limited number of experiments which have been performed on nuclei in this region of the periodic table do not yield information of the levels in the regions of excitation equivalent to that studied for Sc$^{45}$. 
VIII: CONCLUSIONS

The conclusions concerning the physical significance of the observed data have been considered in the chapters in which the data were presented. For this reason such conclusions will not be repeated here, and the discussion will be confined to the annular magnet itself.

Three factors are of importance in evaluating the effectiveness of such an instrument. These are: the accuracy of energy measurement, the resolution of the instrument, and the minimum intensity observable. The experiments of Chapter VI and VII yield information on these factors for the annular magnet in its present state of development. The accuracy attainable in a single measurement of a Q value appears to be approximately \( \pm 0.002 \) Mev for low Q values and slightly larger for higher Q's, as explained in Chapter IV. Greater accuracy may of course be obtained by repeated measurements, when desired. The minimum half-width observed for groups from very thin targets was of the order of 0.8 mm for lower energy observed protons and as small as 0.5 mm for higher energy protons. These figures are to be compared with the average diameter of curvature of 70 cm. On this basis the momentum resolution expressed in the usual manner, \( \rho/\Delta \rho \), lies in the range 875 to 1400. The energy resolution represented by these values lies in the range of 3 to 5 kev, for the range of proton energies used with the magnet. The scandium spectra indicate that with the present techniques the observed background
levels are sufficiently low that groups with a cross section of about 0.1 mb/sterradian may be detected.

The accuracy and resolution of the Rice Institute annular magnet are thus at least comparable, and in some cases better, than any similar instruments in existence at this time. At the present time greater accuracy in the measurements of the excitation energies of excited states of nuclei is probably not necessary. The resolution appears to be sufficient, at least for the fields of study currently envisioned for the magnet. Further improvement in this direction will probably involve a reduction of the solid angle of the magnet, and consequently a reduction in the transmission, which is not desirable at this time.

The category in which improvement of the operation of the magnet may probably be most profitably pursued is in the further reduction of the background, thus permitting the observation of less intense groups than those reported in this thesis. The approach to the background problem has to this point been concerned, as pointed out in Chapters I-III, with reduction of the fraction of the incident beam striking materials in the vicinity of the target. Further effort in this direction will not produce results in proportion to the effort involved, and should probably be directed to the removal of the material which this scattered beam strikes. Since the target slit only serves the purpose of locating the position of the beam for the radius of curvature measurement, a means should be devised for withdrawing the slit for the actual exposure. Steps of this nature are currently being
considered by the annular magnet group and will not be further dealt with here.

The results presented in this thesis have been chiefly concerned with determination of the energy of excitation of states of the nucleus; although, as shown in the beryllium experiments, additional information may sometimes be obtained. It should be noted that, while the annular magnet is primarily designed for such energy determination, its use is not necessarily limited to this type of experiment. It is conceivable that at some future time the magnet will be adapted to such problems as excitation functions and angular distributions. Such use, however, will probably be restricted to cases in which the necessity of high resolution outweighs the disadvantages of the solid angle which for the annular magnet is smaller than that provided by most other means.
APPENDIX

It is a well known geometrical property of the circular orbits of charged particles in a magnetic field, that a parallel beam of monoenergetic particles, entering the edge of the uniform magnetic field normally, will be brought to focus after a deflection of ninety degrees, neglecting second order effects. It may furthermore be shown that a beam entering such a field at an angle $\pi/2 - \eta$, to the normal will be focused after suffering a deflection of $\eta$. This property is shown in Fig. A-1 (a), which is drawn to a greatly exaggerated scale for clarity. The converging of the beam between the traveling slit at $A$ and the target slit at $B$ may then be computed with the simplification of a linear geometry as illustrated in Fig A-1 (b). The linear distance required for the focusing of the beam will be $\rho \eta$, where $\rho$ is the radius of curvature of the beam in the magnetic field. If then the traveling slit has a distance "l" from the edge of the field, and the traveling and target slits are a distance "d" apart, the ratio of the widths of the beam at the target slit, $w_B$ to its width $w_A$, at the traveling slit will be:

$$\text{Ratio} = \frac{w_B}{w_A} = \frac{\rho \eta - (l + d)}{\rho \eta - l}$$  \hspace{1cm} (A-1)

The experimentally observed ratio of these widths is represented by the expression:

$$\text{Ratio} = \frac{w_B}{w_A} = \left(\frac{w_2}{w_1 + R_2 - R_1}\right)$$  \hspace{1cm} (A-2)
Fig. A-1

(A) 

(B) 

\( \eta \) 

\( \rho \eta \) 

\( l \) 

\( d \) 

\( \ell + d \) 

\( w_A \) 

\( w_B \)
where the quantities involved are defined in Chapter III. A comparison of the observed ratio, as computed with Equation (A-2) from a series of several experiments, to the curve from Equation (A-1) is shown in Fig. A-2. In this plot the reciprocal of the ratio, which is the quantity \(\frac{v_A}{v_B}\), is shown. The lower curve (dashed line) in Equation (A-1) is plotted with \(\eta\) equal to the observed asymptotic angle at which the beam enters the magnet, "L" and "d" equal to mean measured values of these quantities, and \(\rho\) equal to the value indicated on the abscissa. The upper curve (solid line) is the lower curve displaced upward by a constant amount to give a reasonable fit to the experimental points.

Two possible explanations may be given for the lack of fit exhibited by the dashed curve. One is that the Equation (A-1) is derived from assumptions which do not hold true in practice. Certainly, the assumptions of a step function for the field, and of the constancy of \(\eta\), \(L\), and \(d\) with respect to \(\rho\) are not completely justified. However, the evaluation of the effect of deviations from the assumed conditions is impossible without attacking the problem in considerable detail.

Another possibility is that the two methods of determining the edge of the beam, described in Chapter III, are not completely equivalent. It seems reasonable to assume that in the visual method the beam may overlap the slit to a greater extent than that required by the current measurement. Such an explanation would validate the constant shift of the curve shown in Fig. A-2. It is quite likely that both of these effects and possibly others could
occur, although it is impossible without a more exact analysis to
differentiate between these effects. However, the general
agreement of the observed dependance of the effect on $\rho$ indicates
that the effect is probably due to the convergence of the beam in
the field. It thus appears justifiable to correct the data on
the basis of Equation (A-2), where it is understood that this
correction is limited in accuracy to an extent indicated by the
spread of the experimental points of Fig. (A-2). The average
deviation of these points is $\pm 0.038$ in the ratio. This implies an
average error of $\pm 0.002$ cm in the micrometer reading difference,
$R_2 - R_1$. Since the quantity $\Delta R_0$ (Equation III-2) is based upon
two such micrometer readings, an average error of $\pm 0.004$ cm is
predicted for this quantity.
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