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ENERGY LEVELS IN IRON, NICKEL, MANGANESE, AND COPPER

BY MAGNETIC ANALYSIS

by

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A THESIS

SUBMITTED TO THE FACULTY

IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Houston, Texas
(May, 1955)
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Acknowledgments
I INTRODUCTION

In the past few years several nuclear theories have been proposed to give the details of nuclear reactions. Generally such efforts, in the absence of a satisfactory understanding of nuclear forces, have resulted in the proposal of models of the nucleus. Experimental efforts usually are directed at testing such models. The success of matching experimental results with the theory of a particular model has been somewhat limited. A model which seems to fit in one area of experimental results is completely unreliable in others, hence it takes several different models to explain all the effects observed. It is to be hoped that additional information or greater precision of measurement will permit the selection of one model as the one best suited to all or most of the facts.

A large number of tests may be applied to a theory on the basis of "established" laws of nature such as the conservation of energy, momenta, and parity. These tests usually are manifest in measurements of cross sections, angular distributions, angular correlations, and energy levels of excited states in nuclear reactions. Measurements of these phenomena, or a refinement of older measurements, therefore can be useful in formulating a suitable theory of nuclear interaction.

One of the things of interest in a quantum mechanical picture of the nucleus is the energy level structure of the excited states. The density and the position of these states
relative to the ground state depends on the nuclear potential
involved, so that a study of precise values of these energy
levels would yield information as to the kind of potential
function in which the particles move. The potential func-
tion, in turn, supplies insight into the forces involved. Ex-
perimen tal research along these lines consists of first ex-
citing the nucleus by means of a nuclear reaction and then
observing the particles which are emitted from the compound
system in its return to a stable condition.

Varied techniques have been employed for the production
of nuclei in excited states. The techniques that are suit-
able vary with the nucleus to be studied and the nature of
the particles which are emitted. Ordinarily, the desired ex-
citation can be produced by bombarding the nucleus with light
weight nuclear particles. If the incident particle is charged
then it is necessary to have a more energetic particle than
if the incident particle was uncharged, since it must penetrate
the repulsive effects of the Coulomb field of the target nu-
cleus. This effect can be eliminated by using neutrons to ex-
cite the nuclei, but if charged particles are used for the
nuclear excitation then it is necessary to have some device
to accelerate them to high kinetic energies.

In the region of light weight target nuclei, a number of
accelerators will suffice. The Van de Graaff and the Cockcroft-
Walton electrostatic accelerators have been satisfactorily
used, whereas for heavier target nuclei various types of cy-
Cyclotrons and linear accelerators have proved useful. In the past few years the development of Van de Graaff accelerators capable of achieving higher energies has led to the experimentation on medium Z nuclei. The Rice Institute 5.5 MeV Van de Graaff generator is suitable for such work and has been used in the experiments to be discussed here to study the excited states in some of the isotopes of iron, nickel, manganese, and copper.
II EXPERIMENTAL CONSIDERATIONS

Dynamics of Scattering

The work presented here treats the scattering of protons from the target nuclei of medium Z. In collisions of this sort a target nucleus of mass $M_0$, charge $Z_0$, which is at rest is bombarded by a particle of mass $M_1$, charge $Z_1$. As a result there is emitted a particle of mass $M_2$, charge $Z_2$, and a residual nucleus of mass $M_3$, charge $Z_3$, which may or may not be the same as the original pair of particles. In such collisions, it can be shown that the energy of the emitted particle is:¹

$$E_2 = \frac{M_0 M_3 + M_1 M_2 \cos 2\theta}{M^2} E_1 + \frac{M_3}{M}$$

$$+ 2E_1 \frac{M_2}{M} \cos \theta \left[ \frac{M_1 M_3}{M_2 M} \left( \frac{Q}{E_1} + \frac{M_0}{M} \right) - \frac{M_1^2}{M^2} \sin^2 \theta \right] \frac{1}{2}$$

where $M = M_0 + M_1 \neq M_2 + M_3$; $E_2$ and $E_1$ is the kinetic energy of the outgoing and incoming particle respectively; $\theta$ is the angle of emission of the scattered particle with respect to the incident beam; and $Q$ is a term which represents the conversion of potential energy of the reactants to kinetic energy. For elastic scattering the ingoing and outgoing particles are the same, and $M_2 = M_1$, and $Q$ is zero. The excitation energy can be determined for inelastic scattering provided the masses of the reactants are known and $E_1$ and $E_2$ can be measured.
On the basis of the quantum mechanical picture of the nucleus, when a particle is scattered from a nucleus there is a greater probability than not that the target nucleus will be left in one of a discrete set of energy states that are characteristic of the target nucleus. Hence, particles scattered from the target will show pronounced energy groups at energies corresponding to these levels. The energies of these levels can be measured by determining a $Q$ for the particle group. The negative of this value is then the excitation energy of the nucleus, and the equation for the determination of $Q$ is:

\[ Q = \frac{M_2 + M_3}{M_3} E_2 - \frac{M_3 - M_1}{M_3} E_1 - \frac{2}{M_3} (M_1 M_2 E_1 E_2)^{\frac{1}{2}} \cos \theta. \]

**The Annular Magnet**

The experimental determinations of $E_1$ and $E_2$ for inelastic scattering of protons from iron, nickel, manganese, and copper have been carried out by use of the Rice Institute annular magnet. The quantity $E_2$ was measured for each discrete group of scattered protons. $E_1$ for each ground state group was determined using equation (1) with $Q = 0$. The masses used were those obtained from mass-spectroscopy data.\(^2\) The $Q$ values for the excited states could then be determined from
equation (2), using \( E_2 \) for the particle group in question and \( E_1 \) from the ground state group calculation.

The magnet in its original form has been described by Klems\(^3\) and subsequent modifications are due to Famularo\(^1\) and Gossett.\(^4,5\) Only a brief discussion will be given here.

The vacuum tube which fits into the gap of the magnet is shown in Fig. 1. The magnetic field is perpendicular to the plane of the diagram. The beam comes in through the entrance port shown in the lower left hand corner of the figure after passing through the slits of the accelerator 90\(^0\) magnetic analyzer. The slit at A, and a slit perpendicular to it which is not shown, serve to define the beam to a rectangular cross section about 3.0 mm high and 0.5 mm wide. This beam then passes through the traveling slit at C. The traveling slit serves to reduce the number of particles scattered from the slit edges at A from reaching the target area. Slit C is movable with a micrometer screw to measure its position, also it is insulated so that the beam striking it can be measured.

In the alignment process, the most intense part of the beam from the accelerator is centered in the target slit D by positioning the magnet on its sliding base while observing the fluorescence of the slit edges of D which are coated with zinc sulfide. Then the slit at A is adjusted to a rectangular shape of the desired dimensions so that the beam passes through the traveling slit and just misses the traveling slit edges. Thus, the traveling slit collects practically all of
the beam which has been scattered from the collimating slit edges at A. This process reduces the number of particles that would otherwise strike the target slit edges. The precise position of the beam is measured with the traveling slit by observing the current reading to that slit's edges. The beam edge is taken as that position of the traveling slit which is determined by the micrometer when 5% of the beam strikes the traveling slit edges. The traveling slit micrometer reading also serves to measure the angle at which the beam strikes the target.\textsuperscript{1,5} The total beam is collected by the Faraday cup F and measured by a current integrator and recorder described by Watt.\textsuperscript{6}

The particles from the beam that are scattered by the target at E in Fig. 1 at a mean angle \( \theta \) to the beam direction are accepted into the angle defined by the slit at J. The slits at 45\(^\circ\) to J slit serve to reduce multiply scattered particles from reaching the detector. The scattered particles are bent to a focus by the magnetic field onto photographic plates used to detect them. The photographic plates rest on a rotatable camera table at K. Eight plates are exposed in the camera before reloading is necessary. They can be rotated in succession into position K without breaking the vacuum seal. The plates used were principally Eastman E\( F \)A type which have a 25 micron emulsion and are provided with or without a coating to protect them from scratches. A few Ilford plates with E\( \gamma \) type emulsion were used.
To determine $E_2$ for a particle group it is necessary to measure the radius of curvature for a particular particle group and the magnetic field. From the product $B\rho$, where $B$ is the magnetic field and $\rho$ is the radius of curvature of the particle, the momentum can be obtained, and the kinetic energy $E_2$ can be calculated from this momentum and the mass of the emitted particle.

The measurement of $\rho$ is determined by measuring three quantities. These are: (1) the distance from the inboard target slit edge to a line on the inboard edge of the photographic plate, (2) the distance from this line out to the particle group on the plate, and (3) the distance from the inboard target slit edge to the inboard beam edge. The three measurements are then summed to give $\rho$. The line on the photographic plate is produced by casting the image of a very fine hot wire from $M$ shown in Fig. 1 onto the photographic plate during exposure, thus causing a black line to appear on the plate on development. The measurement of the distance between the image of the filament and the inboard slit edge is accomplished by placing a mirror in the plate position $K$ and then measuring the distance from the reflected light and the inboard target slit edge. Measurement of this distance is accomplished by two traveling microscopes mounted on a lathe bed so that the reflection and slit edge can be viewed through holes cut into the vacuum tube for this purpose. The measurement to a given particle group from the light line is accomp-
lished on a microscope with a movable calibrated stage after the plates are developed. The number of particles as a function of the distance $X$ from the light line is obtained by counting the number of proton tracks in an area which is 0.132 mm wide parallel to $X$ and 1 cm long perpendicular to $X$. The distance from the inboard slit edge and the inboard beam edge is determined by the readings of the micrometer on the traveling slit and the known dimensions of the target holder and traveling slit. These readings are discussed more fully elsewhere.\textsuperscript{5}

The magnetic field is measured by a proton moment magnetic resonance device. This device has been described by Jones.\textsuperscript{7} The field is controlled and regulated by current variations in the magnet coils. Automatic error signals for the current variations from a fixed current value are obtained from a resistance connected in series with the magnet coils. This error signal is amplified by a d.c. amplifier and applied to the grids of the magnet regulator tubes. The absorption signal from the proton moment device is displayed on an oscilloscope for monitoring the magnetic field. A block diagram for the regulation and control devices is shown in Fig. 2.

The Accelerator

The Rice Institute 5.5 Mev Van de Graaff accelerator is capable of producing beams of high energy positive ions with an energy spread of only a kilovolt or so at maximum bombard-
ing energy. The particles that emerge from the accelerator are bent by means of an analyzing magnet and emerge at either 90° or 45° from one of the two ports available. Voltage regulation on the accelerator is accomplished by means of an error signal resulting from the beam striking one or the other of the insulated slit edges defining the emergent beam. A d.c. amplifier magnifies this signal and applies it to control the corona from needle points to the high voltage terminal. Regulation can be obtained from the error signal produced by the mass 2 spot at the 45° port while simultaneously using the mass 1 beam at the 90° port. This regulation method is ideal for use in conjunction with the annular magnet since for best beam definition on the target a beam spot whose horizontal dimension is small compared to the vertical dimension is most desirable. With the regulation obtained from the mass 2 spot at 45°, the slit there could be adjusted to a very narrow horizontal one giving good regulation. The mass 1 beam could then be used in the experiments in the form of a vertical line by suitable adjustment of the shims on the analyzer pole pieces and by proper positioning of the 90° slit edges.

For experiments of this sort the Van de Graaff type accelerator has an additional advantage. The acceleration energy can be varied to any fixed value between the lowest operating voltage to the peak operating voltage of the machine. This permits a definite advantage over a fixed energy machine such as a cyclotron. This advantage is apparent from
consideration of equation (1).

Suppose that the bombarding energy $E_1$ is constant. Now consider a ground state group of particles ($Q = 0$). If $\Theta = \pi$ then equation (1) becomes

$$E_2 = \frac{M_0 M_3 + M_1 M_2}{M^2} E_1 - 2E_1 \frac{M_2}{M} \left( \frac{M_1 M_3 M_0}{M_2 M^2} \right)^{\frac{1}{2}}.$$

To put (3) in a more useful form, assume elastic scattering where $M_1 = M_2 = m$ and $M_0 = M_3 = M'$. Then:

$$3.'). \quad E_2 = \frac{(M' - m)^2}{(M' + m)^2} E_1 = \beta E_1.$$

Thus for a ground state group of elastically scattered particles at $150^\circ$ $E_2$ is proportional to $E_1$ and the proportionality constant $\beta$ is determined by the masses of the target and bombarding particle. If $E_2$ is plotted as a function of $E_1$ the slope will be smaller for lighter target nuclei. Indeed, if a ground state line is observed at a given $E_2$ for a certain $E_1$ then the value of $E_2$ for the same line at a different $E_1$ can be calculated. Stated differently, the way the lines shift on such a plot identifies the element involved in producing the line. Of course, for heavier elements $m \ll M'$ and $\beta \approx 1$ so that identification of a line becomes more difficult.

The same sort of analysis can be used for the excited states with certain limitations. Equation (1) can always be
used, but generally it is desirable to have available plots of $E_2$ versus $E_1$ with excited states plotted so that a bombarding energy can be chosen to eliminate the possibility of the lines of the excited state coinciding with an $E_2$ of an intense ground state line from target contaminants. Plots of excited state lines can most readily be produced using a point slope form for the plot of $E_2$ versus $E_1$. The slope can be obtained from equation (1) in a more usable form by expanding the term in the bracket in a power series. Here again $\sin \theta = 0$ for $\theta = \pi$. The result is,

\[ 4. \quad \frac{dE_2}{dE_1} = \beta - \frac{1}{M'} \left( \frac{Q}{E_1} \right)^2 + \frac{m(M' + m)}{(M')^2} \left( \frac{Q}{E_1} \right)^3 + \ldots \]

where the terms used are those defined for equation (3). This equation is valid for any inelastic scattering. Sufficient terms can be added in the region of light $M'$ to reach the precision desired for a given $\frac{Q}{E_1}$. In the region of iron, nickel, manganese, and copper the correction to the ground state slope is negligible for $\frac{Q}{E_1}$ of the order of one-half.

The advantage of the above type of analysis with which lines may be assigned to one element or another depending on where they appear in a plot of $E_2$ versus number of tracks, permits in most cases unambiguous assignment of levels in the nuclei studied. Contaminants are readily identified. This is not possible with a fixed energy accelerator unless the angle $\theta$ is varied as a parameter to aid in the assignment of
the mass of the nucleus responsible for a given group of particles.

**Targets**

The targets used in these experiments were prepared in two forms. Thin foils of nickel were used for some of the nickel experiments. In other cases, the target material was evaporated in a vacuum onto thin nickel or carbon foils. These foils were attached to the brass target blanks by means of a thin shellac so that they covered a rectangular hole in the target blank. This hole was larger than the target slit so that only the foil over this opening was exposed to the beam during bombardment.

The nickel foils were prepared from commercially available foils. The two thicknesses of the nickel foils available were $10^{-5}$ inches and $4 \times 10^{-6}$ inches according to the manufacturer's specifications.

The carbon foils were prepared by cracking carbon from methyl iodide onto a hot tantalum filament. This process left a thin deposit of carbon on the filament which could be peeled off the tantalum in the form of a foil. Carbon foils thus produced could be attached to the target blank in the same manner as the nickel foils.

Both carbon and nickel have rather high first excited states, 4.5 Mev and 1.3 Mev respectively, so they are useful as backing materials for studying low lying levels in other
elements. Iron, nickel, copper, and manganese targets were prepared by evaporating thin layers of the metal or metallic oxide onto the carbon or nickel foil after it had been attached to the target blank. In cases where targets were weighed, an aluminum foil and a counterweight foil were placed in the evaporation system. The counterweight foil was shielded from the evaporation, whereas the other aluminum foil was placed near the target blank so that it had the target material evaporated onto it. Weighing the aluminum foil and its counterweight before and after evaporation and measuring the area of material evaporated onto the aluminum foil made it possible to determine the amount of material evaporated onto the target. One of the difficulties of such a process arises with the fact that the target material may react with the filament of the evaporator causing material from the filament to be evaporated also. Corrections for this effect will be discussed along with cross sections in a later chapter. The thick \( \text{Cu}^{63} \) foil used in this experiment was evaporated onto an aluminum foil and its weight was determined. It was then removed for use.
III EXPERIMENTAL RESULTS

General

The data presented in this thesis are the results of experiments which were conducted over a period of approximately a year. During that time the magnet and experimental procedures were subjected to considerable change. In particular, the major problem to be solved was the reduction of the background due to the large number of degraded energy protons. This background is due principally to the scattering of protons from the target holder and slit edges. The number of such protons hitting the slit edges is determined by the alignment procedure. If particles are scattered at small angles from the slit edges defining the incident beam, and if such protons can hit the slit edges rather than pass through the slit then these protons may be scattered into the acceptance angle of the spectrometer and be detected. The protons scattered by slit edges will largely be particles of degraded energy and thus may obscure weak inelastic groups from the target. The alignment procedure used to prevent particles from striking material other than the target has been discussed in Chapter II. The background is very sensitive to proper accomplishment of the alignment and is thus dependent on the skill with which the alignment is made. The background problem is discussed in detail by Gossett and is mentioned here only to explain the reason for background variations.

There is another problem which is related only to the
target material. Under the influence of bombardment considerable heat may be produced in a concentrated region on the target. Since of necessity the foil which supports the target is thin, conduction away from this area may be small. As a result the target deteriorates from its original condition. Such effects are unusually apparent with a high resolution instrument of this sort and must be taken into account in the final analysis of the data.

The data are shown in Fig. 3 to Fig. 11. Actually, additional data were used in the final analysis, but those presented are typical and contain the most complete spectra. The quantities plotted are the number of counts per sweep of 0.132 mm at a given \( B \rho \) as the ordinates and the product \( B \rho \) as the abscissae. Along the top of each plot is a non-linear scale of energy \( E_2 \) to facilitate energy comparisons. The particle groups have been identified by the symbol representing the element from which it arises. An asterisk indicates the group is an excited state in the nucleus except in Fig. 3 where the reaction is indicated for each line. On each plot is given the reaction studied. In addition, the bombarding energy \( E_1 \) is indicated. \( E_1 \), where possible, was the value computed from the ground state group of the target whose excited states were studied. In each case these could be compared to values of \( E_1 \) obtained from the known contaminants on the target. Normally such values of \( E_1 \) agreed within 2 or 3 kilovolts.

Basically, the experiments were conducted in order to
find precise values for the energy levels of the seven nu-
clei. However, additional information on cross sections for
inelastic scattering was also obtained. It should be point-
ed out that cross sections were not the primary purpose of
the investigations and that the data necessary for very ac-
curate calculations were not taken. Nevertheless, any in-
formation about cross sections in the kind of reactions de-
scribed is of interest since so little information is avail-
able at this time. Experimentally, the cross section $\sigma$ for
a particular reaction can be found by measuring the quanti-
ties on the right side of the equation

$$
5. \quad \sigma = \frac{Y}{N_0 t \Omega},
$$

where $Y$ is the number of particles detected in the group, $N_0$
is the number of particles incident during the bombardment,
$t$ is the number of target atoms per cm$^2$, and $\Omega$ is the solid
angle subtended by the detector with respect to the target.
The yield can be measured directly by counting the number of
proton tracks in a given line. $N_0$ is computed from the re-
corded number of current integrator counts from the calibrated
current integrator and the proton charge. The value of $t$ may
be calculated by weighing the targets or by use of the target
energy thickness measured with the spectrometer in conjunction
with incremental range–energy relationships for the target ma-
terial. Thus, for weighed targets $t$ can be determined in two
ways. \( \Omega \) can be calculated geometrically from the dimensions of the detector and the spectrometer tube, but is probably more accurately estimated by measuring the yield of a reaction of known cross section, since exact geometrical paths of the protons are difficult to measure in the spectrometer. A more detailed discussion of this measurement will be presented with the data on cross sections.

The Isotopes of Iron

Spectra for the scattering of protons from iron are shown in Fig. 3 to 5. Fig. 3 shows results of one of the first experiments performed. In this experiment the alignment procedure which was used to obtain later spectra was not used, hence the low momentum region of the spectrum shows a rather high background. The proton group due to the 0.545 Mev excited state in Fe\(^{56}\) is clearly evident near the oxygen groups. The double peaks from oxygen arise from the front and back surfaces of the carbon foil used. The weight of the target was \( 2.0 \times 10^2 \mu g/cm^2 \pm 25\% \). Below the oxygen groups are ground state peaks of the carbon isotopes. The C\(^{13}\) peak is to the right of the intense C\(^{12}\) peak. C\(^{13}\) is about 1\% in natural abundance, hence on this basis the top of the C\(^{12}\) peak would be about \( 10^4 \) counts high. The very narrow peak just below the ground state group of the iron is possibly sulfur from the zinc sulfide used on the target slit edges. It will be noted that a small peak appears on the low momentum
side of the iron ground state. This peak is attributed to elastic scattering from Fe$^{54}$ which is about 6% abundant in natural iron. Actually this single peak is not statistically significant, but the repeated recurrence of the peak where different iron targets were used leads to the conclusion that it is real. The separation of these peaks gives an idea of the resolution of the instrument in this mass region of target nuclei.

The bombarding energy $E_1$ was 5.725. This energy was determined from the oxygen peak. This peak was on the same photographic plate as the Fe excited state. $E_1$ determined from the oxygen was considered more accurate than the Fe ground state line.

Fig. 4 shows spectra of targets made from natural iron oxide at a lower bombarding energy. The top part of the figure is the spectrum of a 95 $\mu g/cm^2$ target on a carbon foil. The foil either had oxygen dispersed through it or the oxide reacted with the carbon to reduce the oxide to free iron and CO$_2$ under the influence of heat from the incident beam. The iron ground state structure seems to bear out this conclusion. The iron excited state has now shifted below the oxygen in conformity with the previous discussion of how a line should vary in momentum, relative to other lines, if $E_1$ is changed.

Various contaminants were observed; among these were zinc, sulfur, and tungsten. Presumably, the tungsten evaporated along with the evaporation of the oxide when the target
was made. A correction was applied to the weighed target thickness to account for this tungsten. This correction consisted of calculating the amount of tungsten from the yield and known cross section for Rutherford scattering and then subtracting it from the total weight. The correction is considered fairly reliable since $E_1$ is well below the Coulomb barrier in tungsten. Checks with crude calibrations of the target evaporation system confirm this conclusion.

In the interest of locating any other states that might be present in the region of excitation considered, the experiments were repeated with a target on a nickel backing in the same region of excitation as that blanked out by the thick oxygen and carbon peaks. The target was about 50 $\mu$g/cm$^2$ from the calibration of the evaporation system. These data are shown in the bottom half of Fig. 4. Note that the Fe$^{56}$ state is still below the oxygen, but that in addition there are N$^{14}$ contaminant lines present. These lines are N$^{14}$ on front of the target and behind it. They appear on other spectra as well as here so that the identification is probably reliable. No other states appear above background intensity.

Fig. 5 shows the spectra for a target of iron oxide enriched in the Fe$^{54}$ isotope. This enrichment was such that Fe$^{54}$ was about 95%, Fe$^{56}$ about 4%, and Fe$^{57}$ about 1%. The bombarding energy is approximately the same as for that in Fig. 4. The target condition was worse than that of the natural iron target. Long tails are in evidence on the iron and sul-
fur ground state lines. These tails are attributable to the fact that the traveling slit edge had become loosened and changed its position during the bombardment. It was replaced into its proper position after the plate on which the sulfur tail appears.

The 0.845 Mev level does not appear below the oxygen as it did in Fig. 4, thus the state is attributed to Fe$^{56}$. However, there is a state below the carbon elastic group which corresponds to an excited state in Fe$^{54}$ at 1.413 Mev. This line does not appear on Fig. 5, therefore the conclusion is that it is a state in Fe$^{54}$. Additional data were taken using a target backed by a nickel foil as in the previous case. The region of excitation obscured by the oxygen and carbon elastic groups was studied, but $E_1$ in this case was 5.253 Mev. This spectrum shows a very doubtful line between C$^{13}$ and C$^{12}$. It would correspond to a level at 1.132 in Fe$^{54}$, but is most likely associated with the excited state in some contaminant on the basis of its intensity. The background on this spectrum is very low and is indicative of the background possible by using the alignment procedure discussed previously.

The Isotopes of Nickel

The nickel spectra are presented in Figs. 6 and 7. Fig. 6 shows the results obtained by bombarding a nickel foil. The top curve is a composite plot at the same bombarding energy of two thicknesses of foil. The spectrum to a point just be-
Figure 6
low the carbon elastic peak is the yield from a foil of $10^{-5}$ inch thickness and that below is that obtained from a $4 \times 10^{-6}$ inch foil. These values are not in good agreement with the observed thicknesses which will be found in Table I. The spectrum shown in the lower part of Fig. 6 is from a $10^{-5}$ inch foil at a higher bombarding energy. The diminished carbon elastic peak is due to the fact that the plate was counted past the point where the number of counts per sweep was reliable. The carbon peak was counted to show its relative position at a different bombarding energy. This peak occurs at around 17 or 18 mm from the light line. None of the data from plates in normal spectra are used past the 15 mm point. Contaminants were rather abundant apparently in the form of chloride salts of the metallic contaminants. The lines are all thin with one exception. This is the line that fits elastic scattering from aluminum. This line is thicker than it should be if it is a contaminant from the front surface. It most likely is aluminum distributed throughout the nickel target. However, this line has never been observed again in all the experiments where nickel backers were used. The exact mechanism by which some of the contaminants appear on the targets is not understood.

Fig. 7 shows partial spectra from separated isotope targets of Ni$^{58}$ and Ni$^{60}$. The isotopic abundance ratio in these targets is 98.36% Ni$^{58}$ to 1.52% Ni$^{60}$ in the Ni$^{58}$ target and 98.51% Ni$^{60}$ to 1.45% Ni$^{60}$ in the Ni$^{60}$ target. These spectra
**Figure 7**

- **Ni^{60}_{(P,P)}**
  - $E_i = 4.626$ MeV

- **Ni^{58}_{(P,P)}**
  - $E_i = 4.634$ MeV
show that the 1.453 state and the 1.329 state are from Ni$^{58}$ and Ni$^{60}$ respectively. Both of these lines appear in Fig. 6 since both isotopes are present to a substantial percentage in natural nickel. The tungsten ground state line, similar to the one shown in Fig. 7, was mistaken for the iron ground state line in an experiment just preceding the nickel experiment. $E_1$ for the nickel experiment was based on the iron experiment, hence instead of the nickel ground state, only the tungsten ground state appeared on the plates exposed.

**The Manganese Isotope**

The data on manganese is not very complete. The only information is a complete spectrum at 4.776 Mev and about three plates which show the ground state and 0.126 Mev state at 5.127 and 5.506 Mev. The spectrum and a plot of the data of one of these plates is shown in Fig. 8. The spectrum shows the 0.126 Mev manganese state only weakly if at all. If the state were present it would fall under the $K^{39}$ line in the spectrum. There are a few high points on the front edge of the potassium line. This leading edge is taken as the manganese line and included in the computation for the excitation energy of the state. This is not too important in the final value of the energy. If these data were disregarded, then the mean energy of the level is 0.127 Mev. It is of course possible that other states exist under the oxygen and
carbon lines. This possibility could not be excluded without doing the experiment at a different bombarding energy.

The Copper Isotopes

Fig. 9, 10, and 11 show the data from copper targets. The copper targets were the most reliable ones used. Copper does not react with the heater filament in the evaporation system so no corrections were necessary to account for tungsten evaporated during the process of making the targets.

A 129 \( \mu \text{g/cm}^2 \) Cu\(^{63}\) target on a nickel backing has a spectrum that is shown by the complete spectrum in Fig. 9. The abundance of this isotope in the target was 99\%. The spectrum is complex showing many contaminants. Again these appear to be metallic chlorides. The nickel ground state and the two nickel excited states, of course, appear as do the oxygen and carbon elastic groups from the front and back of the nickel foil. The Cu\(^{63}\) ground state is well resolved to the right of the nickel ground state and is thick enough for reliable calculation of the target thickness. There are five lines which are attributable to Cu\(^{63}\). Some of these lines are known from other data and some are unreported. These lines appear at 0.669, 0.962, 1.325, 1.411, and 1.546 Mev excitation in Cu\(^{63}\). The spectrum has some plates with higher background than others. Background variations were most probably due to variations of the alignment as each plate was exposed. The 1.546 state was evident at the low bombarding
Figure 9

Cu$^{63}$ (P,P)

$E_1 = 4.619$ MEV

Cu$^{63}$ (P,P)

$E_1 = 5.607$ MEV
energy only because of the extremely low background on the plate on which it appeared. Background statistics did not permit observation of this state on the plate on which the Ni$^{58}$ excited state appears. Also, the plate immediately above the 1.325 state has a rather high background. Nevertheless, the states observed were all clearly present.

The lower part of Fig. 9 shows the results of bombarding the pure Cu$^{63}$ foil that was mentioned in the previous chapter. The thickness of this foil was 410 $\mu$gm/cm$^2$. The purpose of this experiment was twofold. First, it was desirable to search for states in the region where the background was high or where Ni excited states had appeared in the previous spectrum. Secondly, it was desirable to bombard the target at a higher energy to confirm the states previously found. These data confirmed without question the existence of states at 0.669, 1.411, and 1.546 Mev. They leave in doubt the state at 0.962 and 1.325 Mev since these latter lines fall under oxygen and carbon peaks. The 0.962 Mev state is well known; thus only the 1.325 state is questionable. However, if we consider the structure of the carbon line from the back side of the foil along with the fact that the base of this line is rather broad we may conclude the state is there. The high points on the leading edges of the carbon peak from the back target surface are believed to be due to the Cu$^{63}$ state. The energy so calculated gives the same value for the energy of the state in Cu$^{63}$ as did the previously discussed experi-
ment. Further, there are no known contaminant lines to be expected in this momentum region.

Data for Cu$^{65}$ are shown in Figs. 10 and 11. The top spectrum in Fig. 10 corresponds to the top part of Fig. 9. Since a separated isotope of about 99% enrichment in Cu$^{65}$ was used for the target, the absence of the lines observed for corresponding Cu$^{63}$ spectrum show that the states observed were in Cu$^{63}$. No evidence was found for a state in Cu$^{65}$ at about 1.12 Mev.$^6$ Here the N$^{14}$ line could possibly cover such a state. Another state which is reported at 1.49 Mev$^6$ was not found. This line should appear just below the Ni$^{58}$ excited state and indeed there is a line there. But other evidence on the nickel level shows that it may have some structure corresponding to resonances in the compound nucleus. (Dr. C. M. Class, Dr. J. P. Schiffer, and Mr. M. S. Moore of the Rice Institute have data on the excitation function of the gamma rays from the 1.45 level in Ni$^{58}$ from the N$^{58}$ (p, p' $\gamma$ ) Ni$^{58}$ reaction that show many sharp resonances that are closely spaced.) Therefore the assignment of a level here to Cu$^{65}$ is subject to question.

In order to resolve the question of the N$^{14}$ covering the 1.12 Mev state and the proper assignment of the 1.49 level, plates were exposed at higher bombarding energy. The results are shown in Fig. 11. The top spectrum is in the region of interest of the 1.12 Mev state and shows the N$^{14}$ peak but no state in Cu$^{65}$. The peak near the left of the curve is prob-
ably C\textsuperscript{13} from the target since it had been used for two experiments and a considerable carbon contamination undoubtedly had been deposited on it. The energy is about 7.5 kev high for the C\textsuperscript{13} elastic line but statistics do not permit reading the extrapolated leading edge of the line to much greater accuracy than this. The second partial spectrum shown in Fig. 11 is from a different target of natural copper on a carbon foil. The isotopic abundance of Cu\textsuperscript{65} has a ratio of about .449 to 1 to Cu\textsuperscript{63} in natural copper. The target used was about 63 \( \mu \text{g/cm}^2 \) of natural Cu, or about 20 \( \mu \text{g/cm}^2 \) of Cu\textsuperscript{65}. The Cu\textsuperscript{63} 1.546 and 1.411 lines are present in this spectrum. The Cu\textsuperscript{65} line at 1.49 Mev of excitation should appear about one-half the way between these two peaks with an intensity of about one-half their intensity if one assumes that the three states have the same probability of excitation. No such state appears.

**Summary of Energy Levels**

The energy levels which have been determined are shown in Table I. Some of the levels which have been determined for each element are computed from data whose spectra are not shown in the thesis. In addition there appears a value for the cross section where they could be estimated. The bombarding energy at which the determination was made is also shown. Isotopes are grouped together, as are the values for a particular energy level, irrespective of bombarding energy. Aver-
age values of the energy levels, with estimated errors, appear below each group. The errors in most cases are assigned on the basis of internal consistency of the data. Where sufficient data are not available for such an analysis, errors of 5 Kev are assigned as reasonable values on the basis of a study of errors in determinations in the past. The manganese state is quoted to ± 7 Kev since errors arising from the unknown position of the magnet after the adjustment of its height between plate exposures cannot be computed.

Cross sections for the various targets were calculated using equation (5). \( N_0 \) and \( Y \) are determined directly from the data and may be considered accurate to about 10%. The thickness \( t \) could be determined by direct weighing, by line width analysis using range-energy relationships, or by use of the calibration on the evaporation system. The copper targets were weighed. In this case, the assumption was made that no contaminants were evaporated along with the target material. Values of \( t \) obtained from the weighed copper targets agreed with the thicknesses determined from line widths within about 25% in most cases. For the iron and nickel evaporated targets the thickness of tungsten was subtracted from the weighed target to obtain the thickness. If possible, line widths were used to determine the thickness of unweighed targets. In those cases where line width analysis was not possible on evaporated targets, the calibration of the evaporation system was used. The conclusion that this determination is fairly accur-
ate was deduced from the agreement in cases where target
thicknesses were also determined by weighing or by line
width. The accuracy of thicknesses from calibration of the
evaporation system is therefore about 25%.

In order to determine the quantity \( \Omega \), data from scat-
tering of protons from carbon were used. The cross sections
for this reaction have been studied by Reich, Russell,
Schiffer, and Phillips. The values which they obtain at
angles up to 165° in the center of mass system were extrapo-
lated to 150° and converted to 150° in the laboratory system.
They also made measurements with the annular magnet on the
same reaction. These experiments were done on a carbon foil
target. Thus in a non-resonant region it is possible to cal-
culate yield and target thickness by means of line width,
height, and the range energy relationship for protons in car-on. The only factor which is unknown in equation (5) is \( \Omega \)
and so may be calculated. The value of \( \Omega \) so obtained is
10^{-4} stearadians. The overall accuracy is estimated to be
20%. This value agrees within 20% with that obtained from
only geometrical considerations of the dimensions of the spec-
trometer slit system. When all errors are considered the val-
ue of cross section may be determined within approximately a
factor of 2 of its true value. The cross section values of
Table I are therefore considered only that accurate.
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GROUND STATE GROUPS

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| Fe$^{56}$ | 0 | - | 4.632 | 95  | 30 |
| Fe$^{54}$ | 0 | - | 4.634 | 93  | 16 |</p>
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IV DISCUSSION OF RESULTS

The results obtained yield the energy levels in stable nuclei at low values of excitation. Level structure at low energies for such nuclei are normally studied in two ways. As in this work, inelastic scattering of particles may be used. A second method of studying low lying states is to study the products of beta decay from unstable isotopes. Energy levels studied in beta decay are those in the stable nuclei that result from the beta decay. In both of these methods the gamma radiation may be studied for those transitions whose energies correspond to the level energy differences of the nuclei which are involved. From the analysis of the gamma rays resulting from beta decay it is frequently possible to make unambiguous assignments of the levels. However, in inelastic scattering experiments, an analysis of the gamma rays is considerably more complicated. The complexity arises due to gamma rays from other processes which may occur when the compound nucleus is formed. For example, capture processes in which gamma rays cascade from energy levels in the compound nucleus with energies of the order of a few Mev complicate the level assignment. Unambiguous assignment of levels from particle groups by means of the spectrometer, in which photographic plates are used, is simplified by the fact that the tracks of alpha particles and deuterons are readily differentiated from the proton tracks. Thus, the residual nucleus is certain in such a reaction. The scattering of protons from states in target contaminants must be consid-
ered, however, when the spectrometer is used.

The beta ray data are compared to those obtained in this work in discussions of each element. In addition, information from inelastic neutron scattering from the target nuclei are considered. Data from these two additional means are about all that is available since most of the nuclei cannot be reached by such reactions as \((d,p)\) or \((d,\alpha)\) studies. However, the study of deuteron induced reactions has been carried out by Enge et. al. with a spectrometer similar to the Rice instrument. They studied reactions leading to \(^{28}\text{Al}\). In this case the reaction has a positive \(Q\) and the emitted particles have energies greater than the ground state group from the target; therefore the spectrometer background is greatly reduced.

\[
\text{Fe} (p,p') \text{Fe}
\]

The data from this experiment conclusively show only one level in each isotope of the two studied. The 0.845 level in \(^{56}\text{Fe}\) is well known from several means.\(^8\) The radioactive decay scheme of \(^{56}\text{Mn}\) and \(^{56}\text{Co}\) indicates a level about 0.85 Mev in \(^{56}\text{Fe}\) which is in agreement with the level shown in Table I.\(^10,11\) The data discussed in this thesis indicate no levels of intensity greater than about 2.5% of the ground state at a bombarding energy of 4.6 Mev to an energy of excitation of about 1.8 Mev of excitation in the residual nucleus. This corresponds to states of about one-half the in-
tensity of the 0.845 Mev state. This is in agreement with
the conclusion that the 0.845 Mev state is the first excited
state within the limits specified. Data from the reaction
Fe (n,n', γ ) Fe show a number of gamma rays at energies lower
than 0.845 Mev. 12 If these low energy gamma rays exist
they may be associated with cascades from higher states.
The number of levels reported by workers for Fe (n,n', γ ) Fe
other than those in reference 12 show that fewer levels are
observed. 13, 14, 15 The annular magnet data indicates that
this is correct.

No levels in the Fe 54 isotope are detected in these data
except the 1.411 Mev state to about 1.7 Mev of excitation to
about the same detection sensitivity as in the Fe 56. The
meager amount of data on the levels in this isotope of iron
does not permit comparison with various experiments on this
reaction. A gamma ray has been reported at 1.37 ± .02 Mev by
Sinclair 16 by means of neutron scattering from an enriched
Fe 54 scatterer. He reports the ratio of the cross sections
of this gamma ray and the 0.845 Mev gamma ray in Fe 56 as
0.6 ± .08. The ratio determined from the cross sections in
Table I is nearer 0.8. It is not possible to exclude a state
at 1.132 Mev in this isotope of iron, but the definite assign-
ment of a state is also not possible. The only evidence of
such a state is shown on the spectrum for this isotope in the
bottom spectrum of Fig. 5. If this line is present it is only
about 7% of the 1.1411 state.
If the 1.132 state is not associated with Fe$^{54}$ then these two nuclei fit the general picture to be expected on the basis of the shell model of the nucleus where the number 28 is a closed shell for neutrons. In this model the neutrons form a closed shell at 28 in the Fe$^{54}$, but for Fe$^{56}$ the less tightly bound two extra neutrons may be more easily excited to produce the Fe$^{56}$ level that is lower.

\textbf{Ni (p,p) Ni}

For nickel again only one level was found for each isotope to an excitation of about 1.7 Mev. These levels in nickel are well known from several experiments. The beta decay of Co$^{60}$ has been studied by many investigators.\textsuperscript{8,17} The gamma rays from the 1.33 state are used as standard gamma ray sources to a large extent in this country. The energy of these gamma rays has been measured by Lind et al.\textsuperscript{18} to high precision by means of a curved crystal spectrometer. They quote a value of 1.3316 $\pm$ .0010 for the first excited state in Ni$^{60}$. The value for the energy of this state quoted in Table I is in agreement with this value within the experimental error.

The Ni$^{58}$ state is not known to such precision. Possibly the best energy determination to the present is that of the Pittsburgh proton scattering group.\textsuperscript{19} They show a level at 1.479 and state an overall accuracy of 20 Kev. Their value is outside the experimental error for the 1.453 state. Agree-
ment on the value of the state in Ni$^{60}$ with the precision value of Lind et. al. lends credence to the level energy as given here for Ni$^{58}$. The comparison of the spectra from the separated isotopes show conclusively that the 1.453 level is from the Ni$^{58}$.

For nickel again the shell theory seems to apply. No states are observed below the 1.3 state in Ni$^{60}$ or the 1.4 state in Ni$^{58}$. The conclusion is again that 28 is a closed shell, this time for protons. In addition, since the neutrons in Ni$^{58}$ are only two in excess of 28 whereas the excess is four in Ni$^{60}$, the higher state observed in Ni$^{58}$ is thus expected to occur. Hence we have reasonable agreement between the case in Fe$^{54}$ where the system is doubly magic except for two proton holes, and the case in Ni$^{58}$ where the system is doubly magic except for two excess neutrons.

**Mn (p,p) Mn**

The manganese data is not conclusive in many respects. The cross section given for the one state is considered almost as accurate as the rest of those measured, however, with regard to additional states, they cannot be excluded in the single spectrum due to the oxygen and carbon peaks. Until additional work is done at higher bombarding energies, the question of such states cannot be settled.

**Cu (p,p) Cu**

Copper has been studied by both beta decay and by
inelastic neutron scattering experiments. The decay scheme for Zn$^{63}$ has been reported.$^{17}$ Levels are reported at many values by the neutron scattering experiments.$^{20,21}$ Many of these experiments were done with natural copper and therefore give the levels in both Cu$^{63}$ and Cu$^{65}$. Beta decay data is used to determine the isotope responsible for the gamma ray.$^{20}$ Garrett et al. have attributed a 1.53 Mev gamma ray to the 1.49 Mev level in Cu$^{65}$ which is given by beta decay of Ni$^{65}$. However, the present results show conclusively a state at 1.53 in Cu$^{63}$.

The results of the Pittsburgh group$^{23}$ show a complex spectra for the inelastic scattering of protons from copper. The numerous lines reported by this group are not tabulated or assigned to any particular isotope of copper. Their data shows several peaks in the regions where lines reported above have been observed; however, they only assign levels in copper at values corresponding to the beta ray data. Presumably unambiguous assignment was not possible since the bombarding energy of their cyclotron was fixed. Heydenburg has reported a level at 0.690 Mev.$^{24}$

The decay scheme for Cu$^{65}$ is known from the beta decay of both Ni$^{65}$ and Zn$^{65}$. Levels are reported at 1.12 and 1.49 Mev.$^{22}$ Further, both levels are reported by the neutron inelastic scattering work. It is thus hard to understand how the levels escape detection. The only evidence of any state in Cu$^{65}$ is the peak that appears on the left side of the Ni$^{58}$
peak in Fig. 10. From other evidence on the nickel peak it is believed that the structure evident there is due to resonance in the compound nucleus. Since the incident proton loses energy as it passes through the foil, peaks may occur when a resonant energy is reached at a point inside the foil thus producing a peak. Therefore the conclusion is that no levels were observed to exist in the Cu$^{65}$ nucleus below about 1.6 Mev excitation. If the cross section for production of the 1.49 state is as large as for levels in Cu$^{63}$ at 1.41 and 1.53 Mev then it should be in evidence on the bottom of Fig. 11. This is not the case.

The elements studied therefore fit the general features of the shell theory of the nucleus except for the Cu$^{65}$. It is hard to understand why five states appear below 1.6 Mev in Cu$^{63}$ and none in Cu$^{65}$ since both are well separated from the 28 shell. A mechanism to explain such results could be associated with the competing decay channels for the compound nucleus. The (p,n) reaction is a possible competition process that might be tested. Brugger has obtained yield curves for the (p,n) reactions using separated isotopes.$^{25}$ These data show a ratio of two, at 4.6 Mev bombarding energy, between yields for neutrons from the two reactions, but at 5.6 Mev the yield is essentially the same for the two processes. The thresholds for the Cu$^{63}$ is about 4.3 Mev and for the Cu$^{65}$ about 2.2 Mev. Each system is at the same order of excitation in the compound system. Thus if one attempts to explain the
low yield of protons in Cu$^{65}$ at 4.6 Mev bombarding energy then the states in the two nuclei should appear at roughly the same intensity for protons at 5.6 Mev. Therefore the neutron yields do not permit explanation of the observed results, and since other charged particle reactions would be unlikely on the basis of Coulomb penetration factors, the competitive decay explanation does not seem to be valid. (No alpha particles lines could be found of sufficient strength to count on the Cu$^{65}$ plates. Two alpha lines did appear at about 10% of the proton intensity on the Cu$^{63}$ plates near the 1.5 and 1.4 Mev proton lines.)

To summarize, the precise values of the low lying energy levels in iron, nickel, and copper have been obtained. Probably the accuracy of these determinations is equivalent to any available to date except for that of Lind et. al.$^{15}$ on the Ni$^{60}$. The use of separated isotopes has made possible the assignment of levels to the particular isotope to which they belong. In copper at least two new levels have been discovered and two recently discovered levels confirmed. Confirmation of one level in Fe$^{54}$ recently reported has also been made. Further work should perhaps be done on manganese, and the effects observed on Cu$^{65}$ should perhaps be subjected to further investigation by the annular magnet and by other means in order to study the reason for lack of excitation of the known states. The cross section measurements are crude but give a fair estimate of intensities to be expected in
such reactions.
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ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. G. C. Phillips for his assistance and advice throughout these experiments. Help obtained from him and Dr. J. P. Schiffer materially aided in taking the data. I am indebted to Dr. T. W. Bonner for encouragement during the early stages of the experiments. To Mr. C. R. Gossett I am grateful for his work in modifying the spectrometer and for helping take data. The entire annular magnet group is indebted to Mr. J. F. Van der Henst and Mr. Earl Harmening for their efforts during the repeated modifications of the instrument. Financial assistance to the author from the A.E.C. is greatly appreciated.