THE DECAY SCHEME OF Fe\(^{59}\)

by

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A thesis submitted in partial fulfilment of
the requirements for the degree of

MASTER OF ARTS

in the Department

of

PHYSICS

We accept this thesis as conforming to the
standard required from candidates for the
degree of MASTER OF ARTS

Members of the Department of Physics

The University of British Columbia

April, 1951
ABSTRACT

The beta and gamma spectra of $^{59}\text{Fe}$ have been examined in a thin lens beta ray spectrometer. Gamma rays with energies of 1.10 MeV and 1.29 MeV were detected using the photoelectric technique with a Uranium radiator.

Using a thin foil as a source, beta groups with maximum energies of 1.77 MeV and 0.45 MeV were found. There was no evidence of a 0.26 MeV group as reported by other workers.

Tentative decay schemes are presented.
ACKNOWLEDGEMENTS

This research has been carried out under a Grant-in-Aid made to Dr. K.C. Mann of the University of British Columbia Physics Department by the National Research Council of Canada.

The author is indebted to Dr. Mann for much advice and assistance rendered throughout the course of the work.

The author is grateful to the British Columbia Telephone Company for the award of a scholarship and to the British Columbia Industrial Research Council and the University of British Columbia for the award of grants for summer work.
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At the present time the physics of the nucleus is only partially understood. No theory has yet been advanced which can explain all of the experimental results. In many cases the experimental data is inadequate. It cannot be expected that a consistent theory of the nucleus will be developed without the assistance of more careful experimental work. One of the most fruitful means of obtaining nuclear data is the study of radiations emitted by natural or artificially produced radioactive isotopes.

Despite the gaps in our knowledge, some properties of nuclei are well known. It has been definitely established that discrete energy levels exist within the nucleus and that by suitable means it may be excited to any of these. The individual neutrons and protons which constitute the nucleus each have a certain spin and parity associated with their wave functions and it is known that these quantities combine to give a resultant spin and parity for the nucleus as a whole. It has been found that certain configurations of neutrons and protons will form a stable nucleus while other configurations are unstable. Unstable nuclei may decay to a stable form by emitting for example a positive or negative electron or by capturing an orbital electron, the exact method depending on the energy available and on selection rules. The residual nucleus is frequently in an excited state and subsequently drops to the
ground state by the emission of one or more gamma rays. The investigation of these particles and quanta often makes possible the calculation of the energies, spins and parities of the various states in a nucleus and the determination of the correct mode of decay. As there are still many isotopes about which complete information is not available, it is important for more experimental work to be done.

(a) **Energy Determinations**

Referring to figure 1, it is apparent that the measurement of the maximum energy of the beta particles allows the determination of the energy difference between the initial state of the original nucleus and a final state of the daughter nucleus, while the measurement of the energies of the gamma rays, if any, allows the determination of the energy difference between the states in the daughter nucleus. If beta particles of more than one maximum energy are emitted, the difference corresponds to an energy difference in the daughter nucleus. With this information it is usually possible to draw a tentative decay scheme illustrating the relative position of the energy levels providing the spectrum is not too complex.
The continuous distribution of energy in a beta spectrum makes it impossible to determine the end point exactly from the graph of number of particles versus energy as is shown in figure 2(a). A different type of plot, shown in figure 2(b), based on Fermi's theory of beta decay, in which the graph intersects the energy axis at a definite angle avoids this difficulty. The theory predicts that the Fermi plot will have a shape which is to some extent dependent on the spin and parity changes associated with the transition, being for instance a straight line in "allowed transitions". This together with a knowledge of the half-life of the isotope and of the total energy involved generally gives a good indication of the spin change.

(b) **Measurements of Internal Conversion Coefficients**

A nucleus in an excited state may decay to the ground state by giving the excitation energy to one of its orbital electrons. This process, known as internal conversion, results
in a line spectrum of electrons being emitted from the source, the energy of the electrons corresponding to the difference between the excitation energy of the nucleus and the binding energy of the K or L orbital electron emitted. These conversion lines are thus superimposed on the continuous beta spectrum as shown in figure 3. The probability for this process to occur depends on the spin and parity changes—that is on the multipolarity of the gamma radiation involved in the alternative method of decay, and on the energy of the transition. The ratio of the number of conversion electrons to the number of gamma rays for a particular transition is called the internal conversion coefficient. Theoretical values for these coefficients have recently been calculated by M.E. Rose with the aid of new computing machines. It is possible therefore to measure these coefficients and by comparing with the theoretical results determine what spin and parity changes may occur. This method has become almost standard practise.

(c) **Coincidence Measurements**

Frequently there are two or more beta groups and many gamma rays associated with the decay of one isotope. It then becomes difficult to draw a unique decay scheme as it is not known
which gamma rays are associated with the various beta groups. Since the lifetime of an excited state is usually extremely short, coincidence counting techniques are used to determine whether or not there are any gammas following betas of a certain energy. Coincidences may be sought between betas and gammas, betas and conversion electrons or between gammas and gammas. The beta-gamma and beta-conversion electron coincidence rates obtained at different beta energies corresponding to the different beta groups help to determine whether gamma rays follow the beta disintegrations. The gamma-gamma coincidence rates determine whether two gammas are in cascade or whether they each result from transitions directly to the ground state. When there are several gamma rays, the various coincidence rates together with the knowledge of the relative intensities of both gammas and betas often makes possible the drawing of a reliable decay scheme where otherwise this would have been impossible.

(d) Measurements on Isomeric States of Nuclei

Occasionally a nucleus may remain in an excited state for an appreciable time. Decay to the ground state proceeds with a definite half-life as in alpha and beta emission. When this half-life is greater than about $10^{-9}$ sec it is possible to measure it by employing delayed coincidence techniques. The channel of the coincidence mixer which handles the beta pulses is delayed for varying times. As this delay is increased, the number of coincidences decreases exponentially corresponding to the decay curve of the excited level. Since the lifetime of an
excited state is dependent in part on the spin change involved in the transition to a lower level, it is possible to obtain in this way an indication of the spin of the excited state.

(e) **Angular Correlation Measurements**

Under certain conditions of spin and parity change, there is a correlation between the angles at which betas and gammas or successive gammas are emitted. Within the last few years a great deal of work has been done in this field and many isotopes have been examined. When there is an angular correlation, comparison with theory sometimes allows the assignment of spin changes to the transition in question.

With most isotopes a combination of the above techniques is necessary to get all the desired data. Most nuclear energy states are as yet unknown either as to energy, sequence or as to spin and parity assignments as a result of the difficulty of interpretation of experimental results. Again, some isotopes have such short half-lives that the measurements themselves are extremely difficult to make; some are difficult to prepare because of the low cross section of the parent material for neutron or proton bombardment while others occur as gases or liquids and are not susceptible to the techniques commonly used with solids. Further investigation in this field is necessary and no doubt new techniques will have to be developed before the body of information is complete.
BETA RAY SPECTROSCOPY

A powerful instrument for studying radiations from radioactive isotopes is the magnetic focussing beta ray spectrometer. This instrument is based on the fact that an electron moving in a magnetic field whose direction is perpendicular to the motion of the electron will move in a circular path whose radius is proportional to the momentum of the electron. Application of the Lorentz force law to an electron moving in a magnetic field yields the equation \( H e v = \frac{m v^2}{\rho} \), where

- \( H \) is the magnetic field strength in gauss,
- \( \rho \) is the radius of the circle described by the electron and \( m, e \) and \( v \) are the mass, charge and velocity respectively of the electron.

Therefore \( H \rho = \frac{m v}{e} \) which is proportional to the momentum of the electron. Since this is the property used in beta ray spectroscopy, it follows that the instrument measures momentum rather than energy. Among the several forms of the instrument are the \( \pi \) or semi circular focussing type, the thin lens and the solenoidal types. These types differ in the form of the focussing employed, and in the source and counter arrangements. In all of them however, the electrons pass from the source through a field which can be varied, and into a counter. The entire path is in a vacuum.
(a) **Description of Different Types**

The \( \pi \) type spectrometer provides a uniform magnetic field, the source and detector being so arranged that the particle trajectory lies in a plane to which the field is normal. Both geiger counters and photographic plates have been widely used as detectors. When a geiger counter is used the field must be varied in small steps to focus particles of different momenta at the counter window. When photographic plates are used only one setting of the field is required and the baffles are removed. The \( \pi \) type of instrument is particularly suitable for low energy work since the total path length may be made small thereby reducing scattering. In addition it is possible to use counters with very thin windows by placing the counters inside the vacuum system and using low pressure filling mixtures.

The thin lens and solenoidal spectrometers are similar in construction and differ only in the position of the baffles and of the magnetic field coils. The thin lens spectrometer is shown in detail in figure 4. The source \( F \) and counter \( J \) are placed at opposite ends of a long tube. The particles pass down the tube and are focussed at the counter by the magnetic field which is parallel to the length of the tube. A system of baffles is arranged as shown(\( C,D,E,G,H \)). These define an annulus down which with the proper magnetic field, electrons of a given energy will pass. The magnetic field used with the thin lens spectrometer is produced by "thin" coils placed at the center of the
tube and focussing takes place only in this region of the path. The theory and design of this type of spectrometer has been described by M. Deutsch, L.G. Elliot and R.D. Evans. A modification of this instrument, the double focussing spectrometer has two coils placed symmetrically about the center of the tube. In the solenoidal spectrometer, the field coils are wound around the tube for its entire length thus producing a field that is axially homogeneous.

(b) Spectrometer Characteristics

The important characteristics of any spectrometer are its transmission and its resolution. Transmission is the fraction of all particles in a given momentum interval which reach the counter. Resolution is the ability to distinguish between particles of different momenta, normally defined as $\Delta P/P$ where $P$ is the momentum. The transmission factor must be large enough to avoid having to use very strong sources or unreasonably long periods of counting. In most work it is desirable to have the resolution as high as possible in order that gamma ray energies can be accurately determined. It should be noted that the conditions of high transmission and high resolution are mutually exclusive in any one instrument so that optimum conditions represent a compromise between these two factors. The transmission and resolution of the solenoidal types are generally higher than for the thin lens but this is accomplished at the cost of greater complexity and higher current requirements.
(c) **Source Arrangements**

The requirements as to size and shape of the source differ somewhat according to the type of radiation being studied. It is always necessary however that the source diameter be small. Large sources affect the resolution adversely. A beta ray source must be thin and must be mounted in such a way that no heavy material is behind it. If these conditions are not met, loss of energy and scattering occur in the source itself and some electrons are backscattered through nearly $180^\circ$ from the backing material. This will result in a distortion of the shape of the spectrum with a resultant distortion in the Fermi plot. The greatest trouble occurs at low energies because the scattering cross section increases as the energy decreases. Thus low energy determinations are difficult to make and the detection and measurement of low energy beta and gamma rays require special precautions against this effect. Suitable materials for the mounting of beta sources are thin sheets of mica, films of material such as collodion and thin foils of light metals. It may sometimes happen that the source becomes charged as a result of emitting electrons and the resultant electric field distorts the spectrum. It is then necessary that the source backing be made conducting. The whole fragile arrangement is usually mounted inside a heavier hollow capsule which can stand the air pressure when the spectrometer is evacuated. When the source is a positron emitter, it is necessary to distinguish between the positive and negative electrons. In the thin lens spectrometer this may be done by inserting a spiral
baffle in the center of the spectrometer tube. Either positrons or electrons are then focused, depending on the direction of the current in the field coils. A typical source arrangement for detection of beta radiation is shown in figure 5(a).

![Diagram of beta radiation source arrangement](image)

**Fig. 5.**

The detection of gamma radiation is accomplished by making use of the photoelectric effect. A radiator of a material with high $Z$ such as uranium or lead is placed at the position normally occupied by the beta source. The same conditions as to diameter and thickness as applied to beta sources apply here except that there is no objection to heavy backing material since most of the photoelectrons are ejected in the forward direction. Generally an absorber of light metal is placed between the source and radiator to absorb all the primary beta radiation. A typical gamma ray source is shown in figure 5(b). Photoelectrons ejected from the inner electron shells of the radiator then pass down the spectrometer and are focused at the counter. The energy of the gamma ray is given by $E_{\gamma} = E_{p,E} + E_{K,L}$, where $E_{p,E}$ is the energy
of the photoelectron and $E_{K,L}$ is the binding energy of the K or L electrons in the radiator material. Usually two peaks corresponding to photoelectrons ejected from the K and L shells are observed. The cross-section for the photoelectric effect falls off rapidly for increasing gamma energy but most nuclear gamma rays are in the energy region where the cross section is sufficiently high for measurements to be made.

(d) **Calibration of the Spectrometer**

The magnetic field is proportional to the current in the field coils since no iron is used in most instruments. In order to calibrate the spectrometer, the current required to focus electrons of one definite energy must be accurately known. The electrons ejected from a radiator by the 0.511 Mev annihilation radiation coming from a positron emitter are suitable for this purpose. Generally it is possible to measure gamma ray energies and beta ray end points to better than one percent and to achieve a resolution of from five percent to as good as two percent in momentum.

(e) **Experimental Apparatus Used in Present Work**

The spectrometer used in the work reported in this thesis is of the thin lens type. The resolution is approximately 3.5% in momentum and the transmission is about 0.4%. The magnetic field is produced by four concentric coils of wire, any number of which may be connected in series. When all four coils are used, electrons of up to 3 Mev may be conveniently focussed at the
counter with the current source available. As the resolution is somewhat better when only the outer coils are used it is generally desirable to use as few as the energy of the particles being investigated will permit. The spectrometer is aligned parallel to the horizontal component of the earth's field, while the vertical component is cancelled out by a pair of large Helmholz coils situated above and below the spectrometer table.

A bell type geiger counter was used as a detector. A flange on the end of the counter fitted into a circular groove in the spectrometer and thus provided a vacuum tight fit. The window was 6 mm in diameter and was covered by a mica sheet of thickness $2 \, \text{mg/cm}^2$ which transmitted electrons of energies above 50 Kev. A "one-shot" multivibrator was used as a quenching circuit. It provided a quenching pulse of 300 volts about $400 \mu \text{sec}$ long.

It is necessary that the current in the field coils be carefully controlled over a considerable range and that it can be easily changed in steps of any desired size. In this laboratory all the current was passed through a bank of thirty eight 6AS7-G's operated in parallel. A small standard resistance was in series with the tubes. The voltage across the standard resistance was compared with that from a Rubicon potentiometer which in turn was calibrated against a standard cell. These two voltages were chopped at $60^\circ/\text{sec}$ by a Brown converter and the resultant square wave was amplified and rectified. The output was fed back to the grids of the 6AS7-G's in the correct phase to correct any difference
in the two voltages being compared. This circuit controlled variations of up to 100/sec. For higher frequencies, an A.C. amplifier was used to feed back a correcting voltage to the grids of the 6AS7-G's. This bank of tubes will pass up to 10 amps. When more current than this was required, some of the current was bypassed through appropriate resistors in parallel with the tubes.
(a) Previous Work

Previous research on Fe$^{59}$ has been done by J.J. Livingood and G.T. Seaborg, and by M. Deutsch and collaborators. Livingood and Seaborg used absorption techniques to measure gamma and beta end point energies. They reported a prominent beta group of energy 0.4 Mev and a much less intense group of approximately 0.9 Mev. Gamma radiation of about 1 Mev was also reported. Deutsch's group used a thin lens spectrometer similar to the one used in this work. They found two gamma rays of energies 1.10 Mev and 1.30 Mev and of approximately equal intensity. A Fermi plot of their beta spectrum showed two groups with end points of 0.26 Mev and 0.46 Mev. These were also of approximately equal intensity. In addition they reported a high energy tail of low intensity on their beta spectrum extending to about 1.1 Mev. They attributed this tail to Compton electrons produced in the source backing and showed that its relative intensity depended on the thickness of the backing. Coincidence measurements indicated that the 1.30 Mev gamma was in coincidence with the 0.26 Mev beta and that the 1.10 Mev gamma was in coincidence with the 0.46 Mev beta.
(b) **Sources Used**

The source used in this research was Fe$^{59}$ prepared by an \((n, \gamma)\) reaction from Fe$^{58}$ in the Chalk River pile of the National Research Council. The radiation time was fourteen days. The iron was in the form of a wire about 1 mm in diameter and 16 cm long weighing one gram. The specific activity was 0.5 mc per gram. About 13 cm of this wire was wound in a tight coil of diameter 1 cm for use as a gamma source. A uranium radiator of thickness 100 mg/cm$^2$ mounted on a brass disc of sufficient thickness to absorb the primary betas served as a source of photoelectrons. Two beta sources were prepared by hammering out a small portion of the wire into a foil. The edges were trimmed so as to provide sources of a diameter of 6 mm. The thicker of these two sources was about 25 mg/cm$^2$ thick while the thinner one was 15 mg/cm$^2$ thick.

(c) **Beta and Gamma Ray Energies**

The gamma ray spectrum is shown in figure 6. Two gammas of energies $1.10^{\pm} .007$ Mev and $1.29^{\pm} .007$ Mev exist. Subtraction of the Compton background shows 'L' photoelectron peaks at 1.10Mev and 1.29 Mev. A very small peak occurs at 0.57 Mev (0.295 on Pot.). Whether a gamma ray of this energy exists is open to question. Certainly it is at the limit of detection of the instrument at these counting rates. The two prominent gammas are in agreement with Deutsch's work.

The complete beta spectrum is shown in figure 8. It
was obtained in two parts. The high energy portion was obtained using all four spectrometer coils, while the intense low energy group shown dotted, required only two coils. This latter group is shown in full in figure 7. The Fermi plots of the two groups are shown in figures 9 and 10. In figure 9 the full line represents the Fermi plot of the low energy group only, the other having been subtracted while the dotted lines are the plots of the two parts of the composite spectrum. The end point energies are 1.77 Mev and 0.45 Mev. It is to be noted that there is no evidence of internal conversion of either gamma ray.

It is clear from figure 9 that there is no evidence for a beta group with a maximum energy of 0.26 Mev as reported by Deutsch. If such a group were present to as little as perhaps 10% of that of the main group there would be an abrupt change in the slope of the Fermi plot at 0.26 Mev. It is not possible that source absorption and scattering just cancelled out this change since the plot of the spectrum obtained with the thinner source is a similar straight line (not shown). Exact cancellation would not be likely with two sources of different thickness. The effect of source thickness to be expected in this connection may be roughly estimated by comparing this beta distribution with that of the 0.32 Mev positron group from Zn$^{65}$. This spectrum was taken in this laboratory in 1949. The source was a zinc foil of thickness 25 mg/cm$^2$. The Fermi plot showed no source distortion above 0.13 Mev. The Fe source used in this work was much thinner yet shows no evidence of a beta group of maximum energy 0.26 Mev.
Fig. 7

FE$^{59}$ Low Energy Beta Spectrum
Fig. 9

FE$^{59}$ Fermi Plot of Low Energy

Beta Group

$\sqrt{N/\sigma}$ vs. $E$ (Kev.)

0.48 Mev.
The group with maximum energy of 1.77 Mev is believed to be due to a small amount of phosphorus impurity in the iron. \( \text{P}^{32} \) has a beta spectrum with a maximum energy of approximately 1.75 Mev. Only a very small amount of impurity is required since the specific activity of phosphorus after fourteen days irradiation is 1200 times that of iron. The half life of \( \text{P}^{32} \) is only fourteen days compared with forty-six for Fe\(^{59} \), thus making it possible to follow the intensity of the group and to determine its origin. Measurements taken nine days apart showed a decrease of almost thirty percent in intensity of the high energy group compared with a drop of about ten percent for the lower energy group. The 1.77 Mev beta group may therefore almost certainly be assigned to \( \text{P}^{32} \). No other impurity could have the observed decay rate and intensity.

Two alternative decay schemes for Fe\(^{59} \) may be postulated on the basis of the above results. The first one shown in figure (a) would mean that coincidences could be obtained between

\[
\begin{align*}
\text{Fe}^{59} & \quad \text{Co}^{59} \\
\beta^- & \quad 0.45 \\
1.29 & \\
1.10 & \\
\end{align*}
\]

(a)

\[
\begin{align*}
\text{Fe}^{59} & \quad \text{Co}^{59} \\
\beta^- & \quad 0.45 \\
1.29 & \\
0.19 & \\
1.10 & \\
\end{align*}
\]

(b)

Fig. 11.
the 1.10 Mev and the 1.29 Mev gamma rays. However E.K. Darby and G. Williams working in this department have found that there are no such coincidences. This scheme must therefore be rejected. The alternative, shown in figure 11(b) requires that a 0.19 Mev gamma be in coincidence with that of 1.10 Mev. No peak corresponding to a gamma ray of 0.19 Mev was obtained in the gamma spectrum shown in figure 6. However, since the binding energy of the K shell of uranium is 114 Kev, any resulting photoelectrons from this transition would have an energy of only about 75 Kev. Any peak would certainly be distorted to the point where detection was unlikely, since the cut-off energy due to scattering and counter window absorption occurs at about 60 Kev with our spectrometer arrangement. It is well to note too that a beta group leading directly to the ground state of Co$^{59}$ would have an energy of about 1.75 Mev and would therefore be masked by the P$^{32}$ impurity.

It would therefore appear on the basis of the evidence of these measurements, that the decay scheme of figure 11(b) best fits the data. It is difficult to understand the non-appearance of the 0.26 Mev beta group as found by Deutsch and co-workers, who on the basis of their evidence postulate the decay scheme shown in figure 12. These workers too, found no evidence of a 0.2 Mev gamma ray which their decay scheme seems to suggest. They concluded from the absence of a direct transition between ground states that the 1.56 Mev beta-transition is highly forbidden and therefore that the spin difference between the ground states of Fe$^{59}$ and Co$^{59}$ is large. They found
no coincidences between gamma-rays, in agreement with the work of Darby and Williams of this department. The two gamma-rays were found to be of approximately equal intensity. The relative intensities of the 1.29 and 1.10 Mev transitions as obtained in this laboratory are estimated to be about 1:1.2.

The scheme shown in figure 11(b) is consistent with Deutsch's findings except for the 0.26 Mev beta-group. It is possible that a high energy beta transition takes place but it will at best, be very weak in comparison to the 0.45 Mev group. In view of the relatively high energy of the transition it is concluded that a beta-transition between ground states is probably forbidden, the degree of forbiddeness being uncertain.

Some tentative conclusions may be drawn by an application of the nuclear shell models of Nordheim or of Mayer to the Fe\textsuperscript{59} and Co\textsuperscript{59} nuclei. According to the first author the 33rd neutron of \textsuperscript{26}Fe\textsuperscript{59} should have a d_{3/2} configuration while the 27th proton of \textsuperscript{27}Co\textsuperscript{59} should have a g_{7/2} term. Measurements on the spin of Co\textsuperscript{59} confirm the latter assignment with a measured value of 7/2. On this basis then, the spin difference is 2 and the parity change is NO (even → even) which makes the transition second forbidden according to the Gamow-Teller section rules. The Mayer nuclear shell model predicts configurations

![Diagram of Fe\textsuperscript{59} and Co\textsuperscript{59} decay](image)
for the ground states of Fe$^{59}$ and Co$^{59}$ to be $f_{9/2}$ and $f_{7/2}$ respectively which would mean a spin change of 1 and parity change NO (odd $\rightarrow$ odd) and hence an allowed transition. The evidence is such that this is unlikely. It is concluded then that the spin of the ground state of Fe$^{59}$ is probably $3/2$ and its parity is even.

Since the Fermi plot of the 0.46 Mev beta-group is a straight line, this transition may well be allowed which would mean that possible spin values for the high energy excited state of Co$^{59}$ could be $1/2$, $3/2$ or $5/2$ with parity even. Since a choice of $1/2$ for this state would mean a spin change of 3 for the 1.29 Mev transition corresponding to electric octupole radiation, such a transition might well be metastable (i.e.-long half-life) and there is no evidence for this. Therefore $3/2$ or $5/2$ is probably a better choice. Since there was no measurable internal conversion of either gamma-ray, estimates of their multipolarities cannot be made. It must be emphasized however that all three spin values are possible, and that without more information on the missing 0.19 Mev gamma little more can be said.
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