RICE UNIVERSITY

GAMMA RADIATION FROM (d, p) AND (d, n) REACTIONS IN NICKEL ISOTOPES

by

Aimar André Rollefson

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I. Introduction

With the development of an improved quantitative theory of the photoelectric effect and its application to the determination of gamma-ray intensities by Hultberg\(^1\), there has been an increase in interest in the external-internal method of determining internal conversion coefficients by use of a beta spectrometer. In this method the internal conversion electrons and the external photoelectrons from a suitable converter material are measured using a beta spectrometer. From the relative intensities of the internal and external conversion lines one may obtain the K-shell internal conversion coefficient using the relationship

\[
\alpha_K = \frac{A_{in}}{A_{ex}} \times \frac{k \times \gamma \times f \times d \times b}{6.025 \times 10^{-4} \times M}
\]

where

- \(A_{in}\) = intensity of the internal conversion line,
- \(A_{ex}\) = intensity of the external conversion line,
- \(k\) = intensity ratio of external and internal sources,
- \(\gamma\) = photoelectric cross section for the K-shell measured in barns/atom,
- \(f\) = Correction factor for the anisotropic distribution of the external conversion electrons,
- \(d\) = thickness of converter in mg/cm\(^2\),
- \(b\) = dimension factor \(6.025 \times 10^{-4}/M\), where \(M\) is the atomic weight of the converter atoms,

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\[ \alpha_K = \frac{Ne}{Ny} \], i.e. the number of K-conversion electrons relative to the number of gamma-rays.

One of the major advantages of the photoelectric method for determination of gamma-ray intensities is that it permits a resolution comparable to that possible in internal conversion work and in this respect is superior to other methods such as the use of a NaI crystal. This improvement in resolution is especially significant in the analysis of complex spectra. Moreover, there is the obvious advantage of using the same experimental arrangement for determination of the gamma ray intensity and for the determination of the intensity of the internal conversion line. In this manner any error inherent in using two different experimental arrangements may be eliminated. The principle difficulty lies in the determination of the \( f \) factor used to correct for the anisotropic distribution of the photoelectrons. In the present work the \( f \) factor used was determined experimentally by measurement of relative intensities of internal and external conversion lines using sources with known internal conversion coefficients.

Using this experimentally determined \( f \) factor, internal conversion coefficients were determined for the ground state transitions of two low lying excited states of Ni\(^{59}\), produced by bombardment of isotopically enriched Ni\(^{58}\) foils by
4.2 Mev deuterons. By comparison of these experimental internal conversion coefficients with the theoretical internal conversion coefficients of Rose$^2$ the multipolarity of the gamma-ray transition may be obtained and hence information may be obtained about the spins and parities of the nuclear energy levels. From these measurements spin and parity assignments have been made for the ground state and first two excited states of Ni$^{59}$. These assignments are consistent with the possible spins and parities calculated by Dalton et al$^3$ from the angular distribution of protons from the Ni$^{58}$(d,p)Ni$^{59}$ reaction.

There are many reasons for interest in reactions involving the various nickel isotopes. Since the nickel isotopes occur just beyond the closing of the $f_{7/2}$ shell for protons at $Z = 28$ and not too far from the closed neutron shell at $N = 28$, a study of the spins and parities of their excited states should provide some test of the validity of shell model predictions. The ground state of Ni$^{59}$ has been shown to be $3/2^-$ in agreement with shell model predictions. Determination in the present work of the multipolarities of the gamma-ray transitions from the first two excited states

$^2$ M. E. Rose, *Table of Internal Conversion Coefficients* (Inter-science Publishers Inc.) New York (1958)

of Ni$^{59}$ indicate spin and parity of 5/2 - for the first excited state and either 1/2 - or 3/2 - for the second excited state.

From an experimental viewpoint there is a practical reason for studying reactions induced by bombardment of natural nickel foils by deuterons since nickel foils are frequently used as backing material in the preparation of other targets. A thorough knowledge of the electron spectra originating in the nickel foil is necessary for the interpretation of other data obtained from targets using nickel foils for backing material. Since gold is frequently used as a converter material, a knowledge of the electron spectra produced when gold is bombarded by deuterons is also quite desirable. The electron spectra obtained when natural nickel foils, with and without gold radiators, are bombarded with deuterons have been observed and analyzed in terms of energy levels in Ni$^{59}$, Cu$^{59}$, Ni$^{61}$, Cu$^{61}$ and Au$^{197}$. From these measurements energy level determinations have been made for various states in the above nuclei. These energies are then compared with those obtained from observation of the proton groups obtained from the Ni$^{58}$($d,p$)Ni$^{59}$ and Ni$^{60}$($d,p$)Ni$^{61}$ reactions$^4$ and with energy levels in Cu$^{59}$ and Cu$^{61}$

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obtained from observation of proton capture experiments.\textsuperscript{5}

Energies of levels in Au\textsuperscript{197} are compared with those obtained from observation of internal conversion electrons following Coulomb excitation of gold by protons.\textsuperscript{6}

\begin{itemize}
\item \textsuperscript{5} J. W. Butler and C. R. Gossett, Phys. Rev \textbf{108}, 1473 (1957)
\item \textsuperscript{6} D. H. Rester, M. S. Moore, F. E. Durham and C. M. Class, Nuclear Physics, \textbf{22}, 104 (1961)
\end{itemize}
II-(A) THE EXTERNAL-INTERNAL METHOD

The magnetic lens spectrometer is particularly suited for measurements of electron spectra and is frequently used for the determination of the relative intensities of internal conversion electron lines. By comparison with a calibrated source of electrons the absolute intensity of the line may be obtained. The observed intensity of a conversion line is given by:

\[ A_{\text{inn}} = I_B C_B = \sum_{\text{LINE}} \frac{N}{B \rho} \lambda(B \rho) \]

where \( I_B = \) no. of electrons emitted per unit solid angle per unit time,
\( C_B = \) spectrometer transmission coefficient,
\( N = \) no. of counts per unit time observed at a given magnetic field \( B \) and radius of curvature \( \rho \).

The determination of gamma-ray intensities by measurement of the photoelectron line is not quite so simple. The observed intensity of the K-photoelectrons is given by:

\[ A_{\text{ex}} = I_Y C_Y C_K d b f \]

where \( I_Y = \) no. of gammas per unit solid angle per unit time,
\( d = \) thickness of converter in mg/cm\(^2\),
\( b = \) dimension factor \( 6.025 \times 10^{-4}/M \),
\( C_K = \) photoelectric cross section for the K-shell (barns/atom),
\[ f = \text{correction factor for the anisotropic distribution of the photoelectrons}, \]
\[ C_\gamma = \text{spectrometer transmission coefficient}. \]

If the same source is considered and it is assumed that in the energy range which separates the internal and external conversion lines the transmission of the spectrometer is constant and hence \( C_\beta \) equals \( C_\gamma \) then the internal conversion coefficient may be directly obtained from the relation:

\[ \alpha_k = \frac{I_\beta}{I_\gamma} = \frac{A_{ln}}{A_{eX}} \tau_k f d \theta \]

Thus the internal conversion coefficient may be obtained directly from the observed relative intensities of the external and internal conversion lines.

The primary difficulty in such a procedure lies in the determination of the factor \( f \) which is dependent on the angular distribution for the photoelectrons and upon the geometry of the spectrometer and source arrangement. Hultberg has measured the differential angular distribution function for the photo-electric effect in Uranium for the energies 412 kev, 662 kev, and 1332 kev. The peaks in the angular distributions occur at angles of 32, 17, and 12 degrees respectively. A theoretical expression for \( f \) for a double focusing beta-ray spectrometer has been derived by Hultberg and Stockendal.\(^7\)

\(^7\) S. Hultberg and R. Stockendal, Ark. f. Fysik 14 565 (1959)
In principle this value of $f$ is valid only for uranium but measurements of the 662 kev transition in Ba$^{137}$ using gold as a converter$^8$ are in excellent agreement with those obtained using uranium as a converter, thus supporting the assumption that no large errors are introduced when applying the uranium angular distribution functions to gold. The theoretical formulae of Hultberg are valid only for the case of a central aperture, as in the case for flat spectrometers, but in principle the angular distribution functions can be applied to helical spectrometers as well if the much more complicated integration over the helical baffle is carried out.$^9$ However the problem of calculating a theoretical $f$ factor becomes exceedingly difficult when one considers a helical spectrometer with the source placed on the converter as is the case in this experiment, and so it was decided to determine $f$ experimentally. Some qualitative arguments about $f$ may be made by considering the effect that observing the electrons at a mean acceptance angle of 40 degrees has upon the $f$ factor calculated in the case of a flat spectrometer with a mean acceptance angle of zero. In the case of the helical spectrometer the acceptance of the electrons at 40 degrees tends to

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8. C. de Vries, E. J. Bleeker and Mrs. N. Salomons-Brobben, Nuclear Physics 18, 454 (1960)

9. R. G. Thomas and T. Lauritsen, Phys. Rev. 88, 969 (1952)
increase greatly the contribution due to gamma-rays emitted at large angles and passing through a greater thickness of radiator and thus increase $f$. For example if the photoelectrons were strongly peaked at 30 degrees one would expect a large contribution due to gamma-rays emitted at an angle of 70 degrees and thus passing through about 3 times as much converter material as the gamma-rays emitted at zero degrees. One would therefore expect the $f$ factor to be much larger for the helical spectrometer than for the flat spectrometer. In either case as the energy of the gamma-ray becomes very large and the photoelectrons are strongly peaked at zero degrees the $f$ factor approaches the secant of the mean acceptance angle of the spectrometer. At very low energies one would also expect a decrease in the value of $f$ since the photoelectrons are more nearly isotropically distributed as the internal conversion electrons are assumed to be. Between these limits $f$ should be a fairly slowly varying function of energy.
II-(B) EXPERIMENTAL DETERMINATION OF THE $f$ FACTOR

In order to determine the factor $f$ experimentally for the intermediate image magnetic lens spectrometer used in the present work, it was decided to measure the K-shell internal conversion coefficient for the 662 kev M4 transition in Ba$^{137}$. This conversion coefficient has been quite extensively measured and the experimental values are in excellent agreement with the theoretical value of 0.093 given by Rose. The source for this experiment was prepared by placing a few small drops of a solution of Cs$^{137}$ in the center of a copper absorber. On the other side of the copper absorber a circle of gold of 1.27 cm diameter, cut from a gold foil of thickness 5 mg/cm$^2$, was glued using a dilute glyptol solution.

The copper serves as an absorber for the internal conversion electrons when one is investigating the external photoelectrons. The source was first placed in the spectrometer with the source spot towards the spectrometer and the internal conversion line measured. Then the source was reversed and the photoconversion line obtained. Finally, in order to determine the background due to photoelectrons from copper, the gold radiator was removed and the same energy region observed again. From the relative intensities of the internal and external lines and the known internal conversion
coefficient, a value of $f$ may be determined from the formula previously given. Using a Cu absorber of thickness 200 mg/cm$^2$ an $f$ factor of 2.83 was obtained. Since in the spectrometer used in this experiment the electrons are observed at a mean acceptance angle of 40°, a large contribution of photoelectrons is expected due to gamma-rays emitted at large angles and hence attenuated by a much greater thickness of copper absorber. Because of this effect it was feared that the $f$ factor measured in this way would be very sensitive to absorber thickness. In order to test this idea a second source was prepared with a copper absorber of thickness 460 mg/cm$^2$ and the $f$ factor determined in the same manner as before. This measurement yielded an $f$ factor of 1.77, thus confirming the strong dependence of $f$ on absorber thickness.

If it is assumed that this variation of $f$ with absorber thickness is linear with absorber thickness then a value of $f$ may be obtained by extrapolation to zero absorber thickness. The rough value of $f$ obtained in this manner was 3.7. Although this is only a rough estimate of the value of $f$, it is in rather good agreement with a much more accurate value of $f$ obtained by W. W. Givens$^{10}$ from a study of the $F^{19}(p,p')F^{19}$

reaction. By measurement of the relative intensities of the internal conversion electrons from a 109 kev transition in $^{19}$F and the photoelectrons using a cadmium radiator, an $f$ factor was determined, using the previously determined internal conversion coefficient for this transition. Since the angular distribution of the photoelectrons is not very dependent on $Z$ the value of $f$ obtained using a cadmium radiator should still be good for a gold radiator. The average value of $f$ obtained in this experiment was 3.53. Since in this case there was no absorber the value of $f$ thus calculated should be considerably more accurate than that obtained from the Cs$^{137}$. However one should keep in mind that $f$ is slightly energy dependent and as a result some caution should be exercised in applying this value of $f$ to measurements made at higher gamma-ray energies. The value of $f$ calculated by de Vries et al$^8$ at 662 kev for a double focusing spectrometer is 1.266 and at 412 kev is equal to 1.226. If it is assumed that in the helical spectrometer the variation of $f$ with energy over the range of interest (100-500 kev) is approximately the same as in the double focusing spectrometer, since the variation in either case is simply due to a slight change in the angular distribution of the photoelectrons, then the value of $f$ at some higher energy may be obtained from the experimentally determined value of 3.53 at 109 kev.
III EXPERIMENTAL PROCEDURE

Apparatus

The source of the deuterons used in the various phases of this experiment was the Rice University 6 Mev Van de Graaff accelerator. An intermediate image magnetic lens spectrometer\textsuperscript{11} was used to obtain the internal conversion electron spectra and the photoelectron spectra. The detector used in conjunction with the spectrometer was a 1 inch, end-window Geiger counter having a 1.4 mg/cm\textsuperscript{2} mica window. Later data, including the data used in obtaining internal conversion coefficients, was taken using a Geiger counter which had been mounted inside the vacuum system of the spectrometer. This was done to reduce the transmission losses which had been previously observed in the detection of low energy electrons.\textsuperscript{12} The spectrometer was equipped with a positron baffle designed to prevent positrons from reaching the Geiger counter while freely passing electrons. The spectrometer gave a momentum resolution of 2.8 per cent using the 1.0639 K-shell internal conversion electrons from Bi\textsuperscript{207} with a corresponding transmission of about 3 per cent. This line and the 662 kev transition in Cs\textsuperscript{137} were used in calibrating the spectrometer.

\textsuperscript{11} Ranken, Bonner, Castellio-Bahena, Harlow, and Rabson, Phys. Rev. \textbf{112}, 239 (1958)

\textsuperscript{12} W. W. Givens, M. A. Thesis, Rice Institute
Targets

The targets used in the various parts of the experiment are given in the following table:

<table>
<thead>
<tr>
<th>Target No.</th>
<th>Material</th>
<th>Thickness mg/cm²</th>
<th>Thickness of Au Radiator mg/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>natural Ni</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>2</td>
<td>natural Ni</td>
<td>2.12</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>Ni⁶⁰</td>
<td>2.20</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>Ni⁵⁸</td>
<td>2.18</td>
<td>2.54</td>
</tr>
<tr>
<td>5</td>
<td>Au¹⁹⁷</td>
<td>2.70</td>
<td>---</td>
</tr>
</tbody>
</table>

The natural nickel foils used in preparing targets 1 and 2 are the same thickness foils commonly used for backing materials in making other targets and therefore the spectra obtained by bombarding them with deuterons is of considerable interest in other experiments. These foils are assumed to contain the stable isotopes of Ni in their natural abundances, principally Ni⁵⁸ (68.0%), and Ni⁶⁰ (26.2%), with small amounts of Ni⁶¹ (1.1%), Ni⁶² (3.7%), and Ni⁶⁴ (1.0%). Of these less abundant isotopes the Ni⁶⁴ would be expected to present the most experimental difficulty since the (d,p) reaction produces Ni⁶⁵ which is a β-emitter with a 2.54 hour half life and therefore considerably increases the background observed in this experiment. Targets no. 3 and 4 are isotopically enriched foils obtained from Oak Ridge. Target no. 3 contains
99.83% Ni\(^{60}\) and target no. 4 contains 99.95% Ni\(^{58}\). Target no. 5 is simply a gold foil of approximately the same thickness as the radiator used in making targets 1 and 4.

The radiators on 1 and 4 were prepared by evaporating gold onto nickel foils. First the nickel foil is mounted onto a plate and covered by a circular ring with a hole of known area (1.27 cm\(^2\)) in the center. The foil is then placed 7 cms above a small amount of gold in a tungsten boat through which a current may be passed. The entire system is placed in a bell jar and evacuated. When a sufficiently good vacuum has been attained a current is passed through the tungsten boat heating it and causing the gold to evaporate and some gold to be deposited on the nickel foil. By weighing the nickel foil carefully before and after the gold has been evaporated, the surface density of the gold may be calculated from the known area of the circular hole.

There are many reasons for the use of gold as a radiator in these experiments. One of the most important reasons is the strong dependence of the photoelectric cross section upon Z. It has been found empirically that the total photoelectric cross section is given by a constant times Z\(^n\), for fixed gamma-ray energies, where n is found to increase from about 4.0 to 4.6 as the gamma-ray energy in-
creases from 0.1 to 3 Mev.\textsuperscript{13} In order to obtain a high yield of photoelectrons one uses a high Z element as a radiator. As an example, if one considers a gamma-ray energy of 300 kev the total photoelectric cross section for gold is 80 barns/atom or $241 \times 10^{-3}$ cm\textsuperscript{2}/gm while the total photoelectric cross section for nickel is only 1.0 barns/atom or $9.5 \times 10^{-3}$ cm\textsuperscript{2}/gm. An additional feature which one desires in selecting a radiator is that the photoelectric is the dominant effect in the attenuation of the gamma-ray. For a high Z element the photoelectric effect is the dominant effect for low energy gamma rays. For gold the photoelectric effect is the dominant effect for gamma-ray energies less than 600 kev. For low and intermediate Z elements, on the other hand, the Compton effect becomes predominant over the photoelectric effect at considerably lower energies. For nickel the Compton effect becomes dominant above 150 kev. For a high Z element the binding energy of the K-shell is sufficiently large so as to insure an adequate separation of the K-shell photoelectron peak and the K-shell internal conversion electron peak from the low or intermediate Z target nucleus. The K-shell binding energy for gold is 80.7 kev while the

K-shell binding energy for nickel is 8.3 kev. One of the reasons for the choice of gold in particular is the absence of many strong lines produced by deuteron bombardment of gold. Deuteron reactions in high Z elements in general have low cross sections because of the Coulomb barrier. The only peaks observed are from Coulomb excitation of well known levels in Au\(^{197}\). Only two internal conversion lines in the region of interest (100 to 500 kev) are of sufficient intensity to cause any concern. For intermediate Z nuclei one has the problem of deuteron induced reactions producing interfering lines from excited states of the product nuclei. In addition many deuteron reactions in intermediate Z nuclei produce electron emitters and thus increase the observed background. A major advantage in the use of gold as a radiator is the ease in which radiators of uniform thickness may be made by evaporation. Using the method previously described the thickness of the radiator may be accurately determined.

**Experimental Procedure**

Preliminary investigation was done using target 1 with a deuteron bombarding energy of 4.2 Mev. Since the natural nickel foil is predominantly Ni\(^{58}\) and Ni\(^{60}\) the following reactions are expected to take place:
There may also be some peaks in the electron spectra from less abundant isotopes of nickel.

In addition one would expect to observe internal conversion electrons from transitions between Coulomb excited levels in Au\(^{197}\).

The electron spectra obtained when target 1 was bombarded with 4.2 Mev deuterons is shown in fig. 1.

In order to determine which of the observed peaks are internal conversion electrons from excited states of nuclei produced in the (d,p) and (d,n) reactions in nickel and which are electrons originating in the gold (either photoelectrons or internal conversion electrons from excited states in Au\(^{197}\)), target no. 2, which has no radiator, was bombarded with deuterons of the same energy. The observed spectra is given in fig. 2.

Next, in order to determine which of the peaks were from reactions involving Ni\(^{60}\) target no. 3 containing isotopically enriched Ni\(^{60}\) was bombarded with deuterons and the spectra shown in fig. 3 was observed.

For the purpose of obtaining internal conversion coeffi-
cients for transitions in Ni$^{59}$ the isotopically enriched Ni$^{58}$ foil, target no. 4 was used and the electron spectra shown in fig. 4.

Target no. 5 was then bombarded with deuterons in order to permit one to subtract out the effects of internal conversion lines in Au from the lines originating in Ni$^{59}$. The electron spectra is shown in fig. 5.
FIG 1
Ni, Au + d

Counts per 
μcoulomb

Electron Energy - keV

A, B, C, D, E, F, G, H, I, J, K, L, M
FIG 4
Ni$^{58}$, Au+d

ELECTRON ENERGY — kev

COUNTS PER COULOMB

100
200
300
400
FIG 5

Au + d

ELECTRON ENERGY — kev

COUNTS PER COULOMB

500 400 300 200 100 0

D
C
IV EXPERIMENTAL RESULTS

In the first experiment using nickel foil with a gold radiator, peaks were observed at electron energies of 110, 147, 179, 199, 258, 275, 292, 301, 409, 457, 469, and 482 kev.

The remaining experiments using natural nickel foils without a radiator and separated isotopes of Ni enable one to determine the origin of the observed electron peaks with the exception of B and G.

The following table gives a summary of these results which will be discussed in more detail later.

<table>
<thead>
<tr>
<th>Peak</th>
<th>Electron Energy kev</th>
<th>Energy of γ kev</th>
<th>Origin of γ</th>
<th>Origin of Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>110</td>
<td>192</td>
<td>Au(^{197})</td>
<td>K internal conversion</td>
</tr>
<tr>
<td>B</td>
<td>147</td>
<td>156</td>
<td>Ni(^{63}) and Co(^{56})</td>
<td>K internal conversion</td>
</tr>
<tr>
<td>C</td>
<td>178</td>
<td>192</td>
<td>Au(^{197})</td>
<td>L internal conversion</td>
</tr>
<tr>
<td>D</td>
<td>199</td>
<td>280</td>
<td>Au(^{197})</td>
<td>K internal conversion</td>
</tr>
<tr>
<td>E</td>
<td>258</td>
<td>340</td>
<td>Ni(^{59})</td>
<td>K photoelectron</td>
</tr>
<tr>
<td>F</td>
<td>275</td>
<td>284</td>
<td>Ni(^{61})</td>
<td>K internal conversion</td>
</tr>
<tr>
<td>G</td>
<td>292</td>
<td>301</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>301</td>
<td>340</td>
<td>Ni(^{59})</td>
<td>K internal conversion</td>
</tr>
<tr>
<td>I</td>
<td>384</td>
<td>466</td>
<td>Ni(^{59})</td>
<td>K photoelectron</td>
</tr>
<tr>
<td>J</td>
<td>409</td>
<td>491</td>
<td>Cu(^{59})</td>
<td>K photoelectron</td>
</tr>
</tbody>
</table>
The energy of the observed electrons is obtained by comparing the position of the electron peak to the position of the K-shell internal conversion electrons in Bi\textsuperscript{207}. The value of the magnetic rigidity, $B\varphi$, for these electrons is well known and therefore the value of $B\varphi$ for the electrons in question can be obtained. The quantity $B\varphi$ is a direct measure of the momentum of the electron and hence one may calculate the electron energy from the measured value of $B\varphi$.

In order to obtain the energy of the electron emitted from the target one must correct for the energy loss in the gold radiator and in the nickel foil. The average energy loss of an internal conversion electron in passing through the nickel foil is obtained by computing the energy lost by an electron passing through a nickel foil of half the thickness of the target. This correction is usually quite small, of the order of 1 or 2 kev. A similar correction is made for photoelectrons produced in the gold radiator. The most accurate determination of the gamma-ray energies is obtained from the internal conversion spectra from a foil with no radiator, since in this case no correction is required for

| K | 257 | 466 | Ni\textsuperscript{59} | K internal conversion |
| L | 467 | 475 | Cu\textsuperscript{61} | K internal conversion |
| M | 482 | 491 | Cu\textsuperscript{59} | K internal conversion |
energy loss in the gold radiator which can be several kev. The energy of the gamma-ray is obtained by adding the binding energy of the shell from which the internal conversion electron originates to the energy of the internal conversion electron. The energy of the gamma-ray may also be obtained from the energy of the photoelectrons, since the energy of a photoelectron emitted from a particular shell of the converter is just equal to the energy of the gamma-ray minus the energy of that shell.

Gamma-ray energies obtained in this manner may then be used for an accurate determination of the energies of excited states of the nuclei under investigation. The energy levels thus obtained are in good agreement with previous results of other experiments. The results may be summarized in the following table:

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Energy Level from Present Experiment</th>
<th>Previous Result</th>
<th>Type of Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni$^{59}$</td>
<td>340 kev</td>
<td>341 kev</td>
<td>(d,p)</td>
<td>4</td>
</tr>
<tr>
<td>Ni$^{59}$</td>
<td>466 &quot;</td>
<td>465 &quot;</td>
<td>(d,p)</td>
<td>4</td>
</tr>
<tr>
<td>Ni$^{61}$</td>
<td>284 &quot;</td>
<td>284 &quot;</td>
<td>(d,p)</td>
<td>4</td>
</tr>
<tr>
<td>Cu$^{59}$</td>
<td>490 &quot;</td>
<td>490 &quot;</td>
<td>(p,γ)</td>
<td>5</td>
</tr>
<tr>
<td>Cu$^{61}$</td>
<td>475 &quot;</td>
<td>468 &quot;</td>
<td>(p,γ)</td>
<td>5</td>
</tr>
</tbody>
</table>

It is estimated that the energy levels determined in the present experiment are accurate to within one per cent.
The energy level diagrams for Ni$^{59}$, Cu$^{59}$, Ni$^{61}$, Cu$^{61}$ and Au$^{197}$ are shown in fig. 6 with the transitions observed in this experiment indicated.

The peak labeled A may be identified as the K-shell internal conversion electrons from a 191 kev transition in Au$^{197}$. Such a transition is known to occur between states at 268 kev and 77 kev. Peak C is the L shell internal conversion line from the same transition.

Peak D is the K-shell internal conversion line from a 279 kev state to the ground state of Au$^{197}$. The L shell internal conversion line from this same transition occurs at the same position as peak E but it is considerably weaker than peak E. Peak E is primarily the K-shell photoelectron line produced by a 340 kev transition from an excited state of that energy in Ni$^{59}$ to the ground state of Ni$^{59}$.

Peak F may be identified from figs. 2 and 3 as a K-shell internal conversion electron line from an excited state in Ni$^{61}$ to the ground state. The K photoelectrons from this transition coincide with peak D.

Since peak G appears in fig. 2 it may be identified as an internal conversion line but since it does not appear in figs. 3 or 4, it is probably due to a less abundant isotope of nickel.
FIG 6
ENERGY LEVELS IN KEV

[Diagram showing energy levels for different isotopes, such as Cu^{61} and Ni^{59}.]
Peak H is a K-shell internal conversion line from the 340 kev transition in Ni$^{59}$ plus a small contribution from the L photoelectrons from this same transition.

Peak I is the K-photoelectron line from a 466 kev transition from an excited state of Ni$^{59}$ to the ground state of Ni$^{59}$.

Peak J is the photoelectron line from a 490 kev transition from an excited state of Cu$^{59}$ to the ground state of Cu$^{59}$ plus an internal conversion line from one of the less abundant isotopes of nickel.

Peak K is the K-shell internal conversion line from the 466 kev transition in Ni$^{59}$ plus the L-shell photoelectrons from the same transition.

Peak L is the K-shell internal conversion line from a 475 kev transition in Cu$^{61}$.

Peak M is the K-shell internal conversion line from the 490 kev transition in Cu$^{59}$ plus the L-shell photoelectrons from the same transition.

The origin of peak B is not certain but it is most probably a combination of two peaks. The large decrease in intensity of peak B when the separated isotope Ni$^{58}$ is used and its complete absence when Ni$^{60}$ is used as the target nucleus indicate that the electrons do not originate in Ni$^{59}$, Cu$^{59}$, Ni$^{61}$, or Cu$^{61}$ but are primarily due to a reaction involving
one of the less abundant isotopes of nickel. Peak B is believed to consist primarily of K-shell internal conversion electrons from a 155 kev transition from an excited state of Ni$^{63}$ to the ground state of Ni$^{63}$. The small residual peak observed when Ni$^{58}$ is used is believed to be due to K-shell internal conversion electrons from an excited state of Co$^{56}$, produced in the reaction Ni$^{58}$(d, $\alpha$) Co$^{56}$. 
V ANALYSIS AND CONCLUSIONS

From the electron spectra taken using the isotopically enriched Ni$^{58}$ foil with a gold radiator internal conversion coefficients may be obtained for the 340 kev and 465 kev transitions in Ni$^{59}$ using the external-internal method previously described.

The quantity \( d \) was determined by weighing the Ni foil before and after depositing the gold and dividing the difference by the known area of the gold spot. In this case \( d = 2.54 \text{ mg/cm}^2 \).

For gold \( b = 3.058 \times 10^{-6} \).

The values of \( \tau_K \) were obtained from the tables of White\textsuperscript{14} which give the total photoelectric cross sections. The K-shell photoelectric cross sections were calculated from these total cross sections by using the ratio \( \frac{\tau_{K+L+M}}{\tau_K} \) calculated from the Stobbe formula. The value of this ratio calculated by White at 340 kev is 1.13 and this value should be good for the 465 kev transition also since it is well above the K-binding edge.

The value of \( f \) calculated as previously described was 3.64 for the 340 kev transition and 3.72 for the 465 kev transition.

\textsuperscript{14} G. White-Grodstein, Nat. Bur. of Standards circular 583
transition.

The method used to obtain the areas $A_{\text{int}}$ and $A_{\text{ex}}$ was to take the height of the peak of a plot of $N/B\xi$ vs $B\xi$ and multiply by the width at half height. This method is essentially equivalent to replacing the peak by a Gaussian of the same height and half width since the area obtained in this manner is equal to a constant times the area of the Gaussian. This method neglects tailing which is observed at lower energies on the low energy side of the peak but in this case no appreciable tailing is observed and hence the relative intensities obtained in this manner should be equivalent to those obtained by taking the actual areas.

The values of the internal conversion coefficients thus obtained are given in the following table along with the theoretical K-shell internal conversion coefficients of Rose.

<table>
<thead>
<tr>
<th>Energy of $\alpha$ (keV)</th>
<th>$\alpha_{\text{Expt}}$</th>
<th>$E_1$</th>
<th>$M_1$</th>
<th>$E_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>$1.66 \times 10^{-3}$</td>
<td>$1.20 \times 10^{-3}$</td>
<td>$1.90 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>465</td>
<td>$9.3 \times 10^{-4}$</td>
<td>$5.2 \times 10^{-4}$</td>
<td>$9.1 \times 10^{-4}$</td>
<td>$1.88 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Since the $K/L$ ratio for the internal conversion lines is about 12 and moreover the $L$ line is about 8 keV higher in energy than the $K$ line it will not interfere very much
with the K line and hence the experimental internal conversion coefficient is essentially the K-shell internal conversion coefficient. The experimental internal conversion coefficients are estimated to be accurate to within a factor of 2 or better, with the principal source of error being in the $f$ factor. The experimental internal conversion coefficient for the 340kev transition is most consistent with an M1 transition although the theoretical internal conversion for an E1 transition is also well within the estimated experimental error. The experimental internal conversion coefficient for the 465kev transition is also most consistent with an M1 transition although once again the possibility of an E1 transition cannot be eliminated. Analysis of the angular distribution of the proton groups from the $^{58}\text{Ni}(d,p)^{59}\text{Ni}$ reaction gives possible spin and parity assignments of $5/2^-$ or $7/2^-$ for the 340kev level and $1/2^-$ or $3/2^-$ for the 465kev level. Since the ground state of $^{59}\text{Ni}$ is known to be $3/2^-$ a spin and parity assignment of either $1/2^-$ or $3/2^-$ to the 465kev level would be consistent with the stripping analysis and with the results of the present experiment, since either assignment would give an M1 transition to the ground state. An assignment of $5/2^-$ to the 340kev level would be consistent with the stripping results and the present experiment, since this would also give an M1 transition to the ground state. It is hoped that further experiments will yield better values of $f$ so that more accurate internal conversion coefficients may be obtained, thereby enabling one to chose between M1 and E1 transitions from the internal conversion coefficients alone.
In order to obtain more accurate results using the external-internal conversion method one must know the angular distributions of the internal conversion electrons, the gamma rays, and the photoelectrons. If these angular distributions were all known, then much more accurate internal conversion coefficients could be obtained.
VI. REFERENCES


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