INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®
NOTE TO USERS

This reproduction is the best copy available.

UMI
THE ENERGIES OF SOME NUCLEAR GAMMA - RAYS

C. E. Mandeville
The Rice Institute
May, 1943
THE ENERGIES OF SOME NUCLEAR GAMMA - RAYS

INTRODUCTION

The determination of the energies and the relative intensities of the gamma - rays emitted by radioactive nuclei, natural and artificial, has been a perplexing problem in the field of nuclear physics. Gamma - rays may be absorbed in copper and lead, and from the absorption coefficients thus obtained, the energy of the gamma - rays may be calculated. This method has proved to be very unsatisfactory, since when more than one gamma - ray is present, the absorption coefficient is usually characteristic of the energies of the several different gamma - rays present. It is also known that when gamma - rays fall upon matter, "recoil" electrons are ejected. This phenomenon may be explained by regarding the gamma - rays as small packets of energy termed quanta or photons. The electrons are assumed to be knocked out of matter when these quanta collide with them, and a determination of the energy of the ejected recoil electrons gives the energy of the incident quanta.

A theoretical explanation of the behavior of these recoil electrons, sometimes referred to as Compton recoils, was first given by A. H. Compton. The photon of reduced energy and the recoil electron are given off at angles to the path of the incident quantum as indicated in the following drawing:

(path of incident photon)  (path of recoil electron)  (path of photon of reduced energy)
Compton has shown that the kinetic energy of the recoil electron is given by

\[ E_e = \frac{\hbar \nu (2\alpha \cos^2 \theta)}{(1 + \alpha)^2 - \alpha^2 \cos^2 \theta} \]

\( \nu \) = frequency of the gamma-ray
\( \alpha = \frac{\hbar \nu}{m_0 c^2} \)
\( \hbar \) = Planck's constant
\( m_0 \) = rest mass of the electron
\( c \) = velocity of light

From the expression above, it is clear that the recoil electron receives the largest possible kinetic energy when the quantum makes a head-on collision with it. \( \cos \theta \) is then equal to one.

These recoil electrons may be absorbed in aluminum and their energies determined by the thickness of aluminum required to absorb them. The value of the energy of the electrons gives immediately the energy of the impinging quantum, setting \( \cos \theta = 1 \), and solving for \( \hbar \nu \) in the equation above.

A superior method for ascertaining the energies of these recoil electrons is to obtain their momentum distribution. The end-point of the momentum distribution gives the maximum momentum and corresponding maximum energy of the recoil electrons, and from this result may be obtained the energy of the gamma-rays producing the recoils.

When a charged particle such as an electron moves in a magnetic field perpendicular to the path of the electron, a force, perpendicular to both the magnetic field and the path, acts upon the electron. The magnitude of the force is given by \( \mathbf{F} = q \mathbf{v} \times \mathbf{H} \), \( q \) being the field strength.
\[ e \text{ the electronic charge, and } v \text{ the velocity of the electron. The electron therefore describes a circular path so that} \]
\[ H\nu = \frac{mv^2}{\rho}, \]
\[ \frac{mv^2}{\rho} \text{ being the centrifugal force and } \rho \text{ the radius of the circle.} \]
We have then
\[ H\rho = \frac{mv}{e}, \]
and we see that \( H\rho \) is directly proportional to the momentum. When the velocity \( v \) is comparable to the velocity of light, \( c \), we have from relativity theory that \[ m = m_0 \sqrt{1 - \beta^2}, \quad \beta = \frac{v}{c}. \]
The relativistic expression for the kinetic energy of a fast moving electron is given by
\[ E_e = m_0 c^2 \left\{ 1 / \sqrt{1 - \beta^2} - 1 \right\} \]
Eliminating \( v \) between these two equations, we have
\[ E_e = m_0 c^2 \left\{ 1 + \frac{1}{H\rho c^2 (e/m_0)^2} - 1 \right\} \]
Thus we see that if the product \( H\rho \) is known, \( E_e \) may be determined.

If \( H \) is held fixed, the product \( H\rho \) is obtained by simply measuring \( \rho \). The path of the recoil electron may be photographed in a cloud chamber, and from the picture, \( \rho \) may be determined. About one exposure may be made per minute so that the time required to examine a momentum distribution is very long, and since the number of suitable pictures is usually small as compared to the total number observed, the statistical accuracy is poor.

**THE SPECTROGRAPH**

In recent years, the method of semicircular focusing in a magnetic field has been applied with success to the problem of measuring the momenta of recoil electrons and thus the energy of the associated quanta. This method may be carried out by means of what is termed a magnetic "spectrograph" or "spectrometer". Such an instrument has been developed at The Rice Institute and has been applied to the measurement of the energies of gamma-rays. A schematic diagram of the apparatus is given in figure 1. It is there seen to consist in a flat cylinder of depth 3 cm
Figure 1

The spectrograph
and inside diameter 18 cm. Recoil electrons are ejected from the bottom of the aluminum cup, \( C \), and in order to be counted in the Geiger - Mueller counters \( T_1, T_2, \) and \( T_3 \), must follow a circular path of radius 5.50 cm. When an electron passes through the three counters, a pulse is recorded by electrical circuits designed for that purpose. The cylindrical box is placed between the pole pieces of an electro - magnet; the field is varied, and since \( \rho \) is necessarily 5.50 cm., the number of pulses recorded for a given time interval may be determined as a function of \( H\rho \).

The Geiger - Mueller counters and the entire box are filled with an argon - alcohol mixture at a pressure of 10 cm Hg, the ratio of the partial pressures being about 9. The counters are not in a separate chamber but are open to the entire box. They are 2.0 cm long and are mounted in holes which are bored in a block of lucite. Their diameters are 1.0, 1.5, and 2.0 cm., respectively. The copper cases of the counters, of thickness 0.001 cm, are contiguous, but the wire potentials are independently variable. The varying diameters allow for divergence of the beam of electrons after focusing at the slit \( S_1 \), just beneath the counters. Three other aluminum slits \( S_2, S_3, \) and \( S_4 \) are also placed about the box for collimating purposes. The \( H\rho \) spread allowed by the source width and the slit system is estimated to be about 5 per cent. The lead block, \( B \), employed to shield the counters from gamma-rays coming directly from the source, is 5.8 cm in thickness. The maximum measurable kinetic energy which a beta - particle may have in the field of the Weiss magnet used is about 12 Mev. A typical Rossi circuit and the usual recording meter and thyratron were employed in counting the triple coincidences.

There are four factors other than the decay of the radioactive source for which corrections must be made: (1) increase with increasing
of the $H\rho$ interval over which electrons are counted, (2) variation of the Compton scattering coefficient with energy, (3) dependence of the emission of an electron upon its range in the bottom of the cup which serves as a thick aluminum target, (4) variation with energy of the absorption of electrons in the walls of the counters. This last correction is small for electron energies greater than 1.0 Mev.

Plotting $N/H\rho$ against $H\rho$ serves as a correction for (1). Factors (2) and (3) complicate the determination of the relative intensities of the various components of the gamma-ray spectra. They may be most satisfactorily dealt with, however, by evaluation the relative intensities with the equation

$$\text{Intensity} = \frac{\text{Area under } N/H\rho \text{ plot}}{\text{(Electron range in Al)(Compton coeff.)}}$$

A rough correction for (4) is obtained from known absorption curves (1927 a). The calibration of the apparatus has been verified by observations on the recoil electron spectrum of the gamma-rays from Th(C + C'), (1941 a).

For measurements on gamma-rays of energy less than one million electron volts (1 Mev), it has been found desirable to use only counters $T_1$ and $T_2$ of the spectrograph (see fig. 1). The use of three counters for measurements on gamma-rays of energy less than 1 Mev has been found to lead to an excessive amount of absorption of the Compton recoils of low energy.

Sc$^{48}$

Sc$^{48}$ may be produced by either of the following reactions:

1. $\text{Ca}^{48} + D \rightarrow \text{Sc}^{48} + 2n$

2. $\text{Ti}^{48} + D \rightarrow \text{Sc}^{48} + p$

The first reaction represents the bombardment of calcium by deuterons (D)
to give radioactive scandium (Sc) and two neutrons ($2n_1$). Reaction (2) describes the bombardment of titanium by fast neutrons to produce Sc$^{48}$ and one proton ($p^1$); that is, the neutron may be regarded as entering the Ti$^{48}$ nucleus, knocking out a proton, but remaining in the nucleus to produce Sc$^{48}$. Reaction (1) was produced by the bombardment by deuterons of a crystal of calcium fluoride (CaF$_2$). Reaction (2) was obtained by bombarding chemically pure titanium dioxide (TiO$_2$) with fast neutrons. The half-period of Sc$^{48}$ has been determined by Walke (1940 a). It was found to be $44\pm1.0$ hr. (By half-period is meant the time for any given number of radioactive atoms to decrease by fifty per cent.) The stable isotopes of Calcium are Ca$^{40}$, Ca$^{42}$, Ca$^{44}$, and Ca$^{46}$, and those of titanium are Ti$^{46}$, Ti$^{47}$, Ti$^{48}$, Ti$^{49}$, and Ti$^{50}$. These stable isotopes were of course also present in the bombarded samples, but previous experiments have shown that the radioactive isotopes formed by the deuteron and neutron bombardment of them have half-periods very long or very short as compared to the 44 hr. period of Sc$^{48}$. The momentum distribution of the Compton recoils of the gamma-rays from Sc$^{48}$ is given in figure 2. The Sc$^{48}$ of figure 2 was produced by CaF$_2$ + deuterons. Triple coincidences from the counters $T_1$, $T_2$, and $T_3$ were recorded. The absorption of slow electrons on the interval $0<\mathcal{H}<2000$ is to be noted. In figure 3 is given the momentum distribution of the recoils of the gamma-rays from Sc$^{48}$ produced by the reaction Ti$^{48}$ + $n_1$ $\rightarrow$ Sc$^{48}$ + $p^1$. This curve was obtained with the use of the two counters $T_1$ and $T_2$, double coincidences being recorded. A comparison of the two curves will disclose that the absorption of slow electrons in the counter walls is not so acute in the second case. The ordinates of both curves were observed to decay with the established half-period of Sc$^{48}$.
Momentum distribution of the Compton recoils of the gamma-rays from Sc\textsuperscript{47}. The Sc\textsuperscript{47} of this curve was produced by the reaction CaF\textsubscript{2} + deuterons.

(Figure 2)
Figure 3

Momentum distribution of the Compton recoils of the gamma-rays from Sc$^{49}$. The Sc$^{49}$ of this curve was produced by the reaction Ti$^{49}$ + n → p.
The energy of the gamma - ray taken from the end - point of the recoil electron distribution is found to be $1.35 \pm 0.03$ Mev. Walke (1940 a), using aluminum absorption, had previously estimated the energy of this gamma - ray to be $0.9 \pm 0.1$ Mev. More recently, Hibdon, Pool, and Kurbatov, (1943 b), have obtained the value $1.33$ Mev for the energy of this gamma - ray. They used lead absorption.

$\text{Sc}^{48}$ has also been shown by Walke (1940 a) to emit negative electrons. Recent experiments by G. P. Smith (1942 a) have shown that the maximum kinetic energy of the negative electron spectrum is $0.640$ Mev. It is reasonable to conclude, therefore, that the radioactive $\text{Sc}^{48}$ nucleus decays with the emission of a negative electron spectrum of maximum energy $0.640$ Mev, followed by a gamma - ray of energy $1.35$ Mev. The decay occurs to an excited state of the $\text{Ti}^{48}$ residual nucleus, and the quantum de - excitation of $\text{Ti}^{*48}$ is brought about by the emission of a gamma - ray of energy $1.35$ Mev. An excited level of the $\text{Ti}^{48}$ nucleus may then occur at $1.35 \pm 0.03$ Mev above the ground state. The entire process is described by the following set of reactions:

$$\text{Sc}^{48} \rightarrow \text{Ti}^{*48} + e^-$$
$$\text{Ti}^{*48} \rightarrow \text{Ti}^{48} + \gamma$$

The asterisk indicates that the titanium (48) nucleus is excited.

$L_{\text{La}}^{140}$

Lanthanum has only one stable isotope, $\text{La}^{139}$. If $\text{La}^{139}$ is irradiated by slow neutrons, one neutron is captured with the instantaneous emission of a gamma - ray to form the radioactive $\text{La}^{140}$, having a half - period of 40 hr. $\text{La}^{140}$ has been shown to emit negative electrons, and lead absorption by Weimer, Pool, and Kurbatov (1943 a)
has indicated a gamma-ray at 2.00 ± 0.05 Mev. Chemically pure
La₂O₃ (Lanthanum trioxide) has been irradiated by slow neutrons.
The momentum distribution of the Compton recoils of the gamma-rays
from La²⁴⁰ is given in figure 4. The end-point of the distribution
corresponds to a gamma-ray energy of 2.05±0.04 Mev in
surprisingly good agreement with the above mentioned absorption
value. Heavy atoms such as La²⁴⁰ often decay with positron
emission or K-electron capture as well as by emission of negative
electrons. It is therefore not considered safe to draw any type
of level diagram to illustrate the disintegration of La²⁴⁰, because
so few experiments have been conducted in the investigation of that
isotope.

\[ \text{Sb}^{122} \]

Antimony has two stable isotopes, Sb¹²¹ and Sb¹²³. Both isotopes
have been observed to capture slow neutrons to form Sb¹²² and Sb¹²⁴,
having half-periods of 63 hr. and 60 days respectively. Chemically
pure antimony metal was irradiated by slow neutrons. The irradiation
lasted for a period of about two days so that very little of the
Sb¹²⁴ was formed. One gamma-ray was found to be present, and it
decayed with the half-period of Sb¹²². The momentum distribution
of the recoils of that gamma-ray is given in figure 5. The energy
of the gamma-ray computed from the end-point is 0.83±0.02 Mev
in good agreement with the value 0.96 Mev given by Mitchell, Langer,
and McDaniel (1940 b) who used aluminum absorption. Their beta-
gamma and gamma-gamma coincidence experiments indicated that only
one gamma-ray is emitted in the decay of Sb¹²². They have also
shown that it emits negative electrons. Sb¹²² may thus be regarded
as decaying with the emission of an electron to an excited state of
Figure 4

$H_\rho \times 10^3$ Oersted - cm

Momentum distribution of the Compton recoils of the gamma-rays from $\text{La}^{40}$

(12)
Figure 5

$H \times 10^5$ Oersted cm

Momentum distribution of the Compton recoils of the gamma - rays from Sb

(13)
the Te$^{122}$ nucleus, the de-excitation of which occurs with the
emission of the 0.83\pm 0.02 Mev gamma-ray.

As$^{76}$

Arsenic has one stable isotope, As$^{75}$. On the capture of a slow
neutron, As$^{76}$ is produced. The half-period of As$^{76}$ has been
measured many times and is 27 hr. The gamma-rays from As$^{76}$
have been twice examined with the gamma-ray spectrograph at the
Rice Institute. In both instances gamma-rays at 0.83\pm 0.02 and
2.00\pm 0.04 Mev were found, and the ratio of the intensities is 3.8.
The momentum distribution of the Compton recoils of the gamma-rays
from As$^{76}$ is given in figure 6. Gamma-rays of higher energy and
with an intensity less than 20 percent of the intensity of the 2.00
Mev gamma-ray might have escaped detection. The gamma-rays of
As$^{76}$ have been found to have the energies 1.45, 215, and 3.1 Mev
by Harteck, Knauer, and Schaeffer, (1938 a), using cloud chamber
pairs. Mitchell, Langer, and McDaniel, (1940 b), reported a
maximum gamma-ray energy of 2.05 Mev. It is not surprising that
the 0.83 Mev gamma-ray was not reported in either of the two
foregoing experiments, since its energy is not sufficient to produce
the rest masses of a positron-electron pair, and aluminum
absorption gives only the energy of the hardest gamma-ray present
with any accuracy. The beta-ray spectrum of As$^{76}$ is known to be
complex, and the mean values of the various observed and extrapolated
results give two components with maximum energies 3.0 and 1.0 Mev.
Weil, (1942 b), has shown that the ratio of the intensities of these
two spectra is 3.5. Coincidence experiments of Norling (1938 b) and
Mitchell, Langer, and McDaniel (1940 c) show that the beta-ray
distribution of maximum energy 3 Mev decays to an excited state of the
Se$^{76}$ residual nucleus and that more quanta are emitted per disintegration

(14)
Figure 6

Momentum distribution of the Compton recoils of the gamma-rays from As$^{76}$
Level scheme for $^{76}$Se

Figure 7

<table>
<thead>
<tr>
<th>Energy in MeV</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>3</td>
</tr>
<tr>
<td>2.8</td>
<td>2</td>
</tr>
<tr>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>0.0</td>
<td>0</td>
</tr>
</tbody>
</table>
in cascade with the beta-ray spectrum of maximum energy 1.0 Mev than with the spectrum of maximum energy 3.0 Mev. These results, coupled with the intensity of the newly reported 0.83 Mev gamma-ray suggest immediately the level diagram for $^{76}$Se given in figure 7.

$^{115}$Cd is produced by the irradiation of the stable $^{114}$Cd with slow neutrons. Pure metallic cadmium has been irradiated by slow neutrons. The momentum distribution of the Compton recoils of the gamma-rays from $^{115}$Cd is given in figure 8. The energy of the gamma-ray is calculated to be $0.72 \pm 0.02$ Mev. Cork and Lawson, (1939 a), have given the value 0.8 Mev as the quantum energy of this gamma-ray obtained by the method of cloud chamber recoils. Subsequent cloud chamber and lead absorption experiments by them (1940 c) suggested rather the value 0.55 Mev. The disintegration of the $^{115}$Cd nucleus is complicated and is not as yet clearly understood.

$^{24}$Na

The gamma-rays from $^{24}$Na have been measured many times and the results to be found published in the literature on this subject are many and varied. Richardson and Kurie, (1936 a), reported quantum energies of 1.00, 2.04, and 3.00 Mev with relative intensities 1:1:0.65. Later experiments by Richardson (1938 c) again gave the same values. Kikuchi, Watabe, Itoh, Takeda, and Yamaguchi, (1939 b), reported quanta with the energies 1.46, 0.8, and 2.97 Mev; the intensities of the 1.46 and 3.03 Mev quanta being about equal. Curran, Dee, and Strothers, (1940 d), reported quanta with the energies 1.49, 2.00, and 3.03 Mev, the intensities of the 1.49 and 3.03 Mev quanta being equal. J. Itoh (1941 b) reported only two quanta at 1.38 and 2.80 Mev as did Elliot, Deutsch, and Roberts, (1942 c), at 1.38 and 2.86 Mev. Recent measurements by Mandeville (1942 d) seemed to indicate quanta at 0.84, 1.31, 1.66, and 2.90 Mev. These measurements of $^{24}$Na were the first made with the spectrograph at the Rice Institute. After measurements on the gamma rays from several other isotopes had been
Figure 8

Momentum distribution of the Compton recoils of the gamma-rays from Cd$^{115}$
Momentum distribution of the Compton recoils of the gamma-rays from Na$^{24}$

Figure 9 (19)
completed, it became apparent that the initial experiments on Na$^{24}$ might have been incorrect. NaF was irradiated by slow neutrons, and the measurements on Na$^{24}$ were repeated. The momentum distribution of the Compton recoils of the gamma-rays from Na$^{24}$ is given in figure 9.

It is there apparent that only two quanta are present with energies 1.38 and 2.94 Mev in agreement with the measurements of Itoh and of Elliot, Deutsch, and Roberts. The intensities of the quanta are about equal, suggesting that they are in cascade.

$^{187\text{W}}, \text{Re}^{188}$, and $\text{Ga}^{72}$

Measurements on these elements have indicated that one gamma-ray of energy 0.9 Mev is emitted by tungsten (187); one gamma-ray is emitted by Rhenium (188), its energy being about 1.0 Mev; two quanta are emitted by Gallium (72), having energies of 1.05 and 2.40 Mev respectively.

The editors of The Physical Review received in the fall of 1942 a paper by W. E. Bennett, C. E. Mandeville, and H. T. Richards. It will not, however, be published until after termination of the present war.

ACKNOWLEDGMENTS

The writer wishes to express appreciation for the interest and advice of Professor H. A. Wilson of the Rice Institute. He wishes also to acknowledge the cooperation of the members of the cyclotron group at Washington University, St. Louis, Missouri. They prepared and sent to him the radioactive materials used throughout the course of these experiments.
REFERENCES

1940 a H. Walke, Phys. Rev. 57, 163, (1940).
1941 a C. E. Mandeville, M. A. Thesis, Rice Institute, (1941).
Gamma-Rays from Na$^{24}$

C. E. MANDEVILLE

Reprinted from The Physical Review, Vol. 62, Nos. 7 and 8, pp. 309–312, October 1 and 15, 1942
Gamma-Rays from Na$^{24}$

C. E. Mandeville
The Rice Institute, Houston, Texas
(Received August 10, 1942)

A gamma-ray spectrograph of high resolving power has been employed in measuring the quantum energies and relative intensities of the gamma-rays from Na$^{24}$. The energies thus determined are 0.84, 1.31, 1.66, and 2.90 Mev with relative intensities 0.28, 0.41, 0.45, and 1.00. These results indicate excitation levels in the Mg$^{24}$ residual nucleus at 1.3, 2.9, and 3.7 Mev in partial agreement with experiments on proton scattering by magnesium, but in disagreement with the level schemes suggested by previous gamma-ray measurements.

Measurements were also made on the gamma-radiation of the thorium active deposit. Close agreement with previous results was considered adequate confirmation of the calibration of the spectrograph.

INTRODUCTION

The energies and relative intensities of the gamma-rays emitted from Na$^{24}$ have been studied by several investigators. Their results do not agree very well, and the presence of gamma-radiation in the neighborhood of 2 Mev has been in dispute. This paper contains an account of new measurements of these gamma-ray energies and intensities, and a level scheme for Mg$^{24}$ is suggested. The gamma-rays from Th(C$''+C''$) have also been observed as a check on the accuracy of the method.

THE SPECTROGRAPH

The energies of the Compton recoil electrons arising from gamma-rays were measured by semicircular focusing in a magnetic field. A diagram of the spectrograph is shown in Fig. 1. It is very similar to that described by Curran, Dee, and Strothers. The depth of the magnet box is 3 cm, and its inside diameter is 18 cm. Compton electrons are ejected from the bottom of the cup C and in order to be counted must follow a circular path of radius 3.50 cm. The cup is so inclined that the electrons counted emerge at an angle of about 20° with the bottom of the cup, thus making the effective width of the source small. The Geiger-Müller counters $T_1$, $T_2$, $T_3$, and the entire box are filled with an argon-alcohol mixture at 10 cm Hg, the ratio of the partial pressures being about 9:1. The counters are 2.0 cm long and are mounted in holes which are bored in a block of Lucite. Their diameters are 1.0, 1.5, and 2.0 cm, respectively. Triple coincidences are recorded. The copper cases, of thicknesses 0.001 cm, are contiguous but the wire potentials are independently variable. The varying diameters allow for divergence of the beam of electrons after the focusing at the slit $S_1$, just beneath the counters. The width of this slit is about 3.0 mm. The sides of this slit are strips of brass 2 cm in length, 1 cm in width, and sufficiently thick to stop an electron of 5-Mev energy, thus preventing the counting of particles not focused on the slit proper. Three other aluminum slits $S_2$, $S_3$, and $S_4$ are also placed

![Fig. 1. The spectrograph.](image-url)
in the box for collimating purposes. The center slit $S_2$, the defining one, is 1.8 cm wide, and the lower edge is 5.3 cm above the bottom of the box, thus making recesses into which electrons not entering the counters may drop. The lead block $B$ employed to shield the counters from gamma-rays coming directly from the source, is 5.8 cm in thickness. The $H_9$ spread allowed by the source width and the slit system is estimated to be about 5 percent. The maximum measurable kinetic energy which a beta-particle may have in the field of the Weiss magnet used is about 12 Mev. A typical Rossi circuit and the usual recording meter and thyratron were employed in counting the triple coincidences.

The background of the counters was found to be constant for both Th($C' + C''$) and Na$^{24}$ over a wide $H_9$ interval above the end point of the hardest gamma-ray measured in each case. This background was also equal to the background at $H_9 = 0$. The background at intermediate points was therefore obtained by extrapolation. Since the background was small as compared to the total number of counts observed, any error in calculation of the relative intensities introduced by this procedure would be small.

There are four factors for which corrections must be made: (1) increase with increasing $H$ of the value of the $H_9$ interval over which electrons are counted, (2) variation of the Compton scattering coefficient with energy, (3) dependence of the emission of an electron upon its range in the thick aluminum target, (4) variation with energy of the absorption of electrons in the walls of the counters. This last correction is small for electron energies greater than 1 Mev. Plotting $N/H_9$ against $H_9$ serves as a correction for (1). Factors (2) and (3) complicate the determination of the relative intensities of the various components of the gamma-ray spectra. They may be most satisfactorily dealt with, however, by evaluating the relative intensities with the equation

$$\text{Rel. Int.} = \frac{\text{Area under } N/H_9 \text{ plot}}{\text{(electron range in Al)(Compton coeff.)}}.$$  

A rough correction for (4) is obtained from known absorption curves.$^3$

**Table I. Gamma-rays from Th($C' + C''$).**

<table>
<thead>
<tr>
<th>Energy in Mev</th>
<th>0.21 ± 0.02</th>
<th>1.58 ± 0.03</th>
<th>1.77 ± 0.04</th>
<th>2.66 ± 0.05</th>
<th>3.32 ± 0.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel. Int.</td>
<td>0.14</td>
<td>0.10</td>
<td>0.05</td>
<td>1.00</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Th(C\(^+\) + C\(\)\(\))

Figure 2 is a plot of \(N\) against \(H\rho\) and Fig. 3 one of \(N/H\rho\) against \(H\rho\). The peaks of the outstanding components of the gamma-ray spectrum are clearly evident in the latter case. Their energies and relative intensities are given in Table I. Ellis\(^9\) has reported gamma-rays from Th(C\(^+\) + C\(\)\(\)) at 1.63, 1.80, and 2.62 Mev with intensities 0.08, 0.04, and 1.00. Weak gamma-rays of quantum energy about 3.3 Mev have been reported by several authors. The intensity reported here is somewhat higher than the most recent report by Itoh and Watase.\(^10\) The intensity of the 0.73 Mev quantum agrees closely with that given by these authors.\(^10\)

The clearly separated peaks of the gamma-rays at 1.58 and 1.77 Mev demonstrate the high resolving power of the spectrograph. The sharp rise to a peak and the equally sharp drop to a clearly defined end point from which the gamma-ray energy may be obtained is to be expected with a spectrograph of this type from the nature of the Compton process. It is further interesting to note the shape of the peaks of the gamma-rays of lower quantum energy and lower intensity in the neighborhood of the intense 2.66-Mev peak. This graph is very useful in analyzing the curves obtained from other radioactive sources.

**RADIO-SODIUM**

The gamma-rays of Na\(^{24}\) were initially investigated by Richardson and Kurie,\(^1\) and again by Richardson,\(^2\) the expansion chamber and magnetic field being employed in both instances. Quantum energies of 1.01, 2.04, and 3.00 Mev were reported, and the intensities of the two softer components were estimated to be about equal. Since the sum of their energies was approximately equal to the energy of the third component, it was assumed that levels of 2 and 3 Mev or 1 and 3 Mev existed in the Mg\(^{25}\) product nucleus.

**Table II. Gamma-rays from Na\(^{24}\).**

<table>
<thead>
<tr>
<th>Energy in Mev</th>
<th>0.84 ±0.02</th>
<th>1.21 ±0.03</th>
<th>1.66 ±0.05</th>
<th>2.08 ±0.06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel. Int.</td>
<td>0.28</td>
<td>0.43</td>
<td>0.43</td>
<td>1.00</td>
</tr>
</tbody>
</table>


**Fig. 4. Momentum distribution of Compton recoils of gamma-rays from Na\(^{24}\).**

 Upon the suggestion of Feather and Dunworth,\(^11\) this level scheme was revised, the new assumptions being that gamma-rays of 1 and 3 Mev were emitted in cascade and two rays of quantum energies about 2 Mev were also emitted in a cascade process. Kikuchi *et al.*\(^2\) reported gamma-rays of about equal intensities with quantum energies 1.49 ±0.05 and 2.97 ±0.07 Mev, thus establishing the 4-Mev level suggested by Feather and Dunworth at 4.46 Mev. Later work by Kikuchi *et al.*\(^4\) resulted in the values 1.55 ±0.05 and 2.97 ±0.05 Mev. In both experiments, weak radiation at about 0.8 Mev was also observed.

Curran, Dec, and Strothers\(^5\) have reported the energies 1.46, 2.00, and 3.03 Mev with relative intensities 1.17, 0.27, and 1.00. The most recent measurements\(^6\) have given indication of only two gamma-rays, having energies 1.38 ±0.02 and about 2.80 Mev. These latter authors may have failed to detect any other radiation because of low intensities.

In this experiment, a sodium chloride crystal, activated by a bombardment of several hours by a deuteron current of 0.3 microampere at 2 million volts, was used as a source, the half-life

being 14.8 hr. Radio-chlorine of 37-min. half-life is formed from the deuteron bombardment of Cl\textsuperscript{37} (relative abundance 25 percent). Although the Cl-d-p reaction is known to be very small as compared to the Na-d-p reaction at this voltage, and although measurements were not made until after any radio-chlorine present had decayed by about 5 half-periods, a potassium chloride crystal was bombarded under the same conditions for the sake of comparison. Contributions from radio-chlorine were found to lie well within the statistical probable error of the points of the curve for Na\textsuperscript{23}. Above \( H_p = 4000 \), about 800 coincidences were counted at each point. Below that value of \( H_p \) about 550 coincidences were recorded at each point.

The curve for Na\textsuperscript{23}, \( N/H_p \) against \( H_p \), obtained with the spectrograph just described, is shown in Fig. 4. The results are tabulated in Table II.

These quantum energies and relative intensities suggest that de-excitation of the Mg\textsuperscript{24} nucleus after beta-emission by Na\textsuperscript{24} may occur with the emission of a single quantum of energy about 2.90 Mev or with the emission of quanta of energies 1.66 and 1.31 Mev in cascade. It would seem then that the disintegration energy of Na\textsuperscript{24} is 1 Mev less than that suggested by Feather and Dun-}

worth.\textsuperscript{11} The level scheme is similar to that initially suggested by Richardson and Kurie,\textsuperscript{1} though theirs was based upon different quantum energies.

The quantum of energy 0.84 Mev is probably the weak line first observed by Kikuchi et al.,\textsuperscript{3,4} and is, as they have pointed out, indicative of the emission of a complex beta-ray spectrum by Na\textsuperscript{23}, contrary to the results of Feather and Dunworth\textsuperscript{11} and of Lawson,\textsuperscript{12} who found the beta-ray spectrum to be simple and of maximum energy 1.4 Mev. The results of Table II indicate that the soft component of the beta-ray spectrum is about one-fifth as probable as the more intense distribution of higher maximum energy. A complete level scheme is given in Fig. 5. By means of experiments on the inelastic scattering of protons by magnesium, Wilkins\textsuperscript{13} has assigned excitation energies to Mg\textsuperscript{24} of 1.37, 2.80, and 4.07 Mev in partial agreement with the results reported in this paper.

It seems possible that other investigators have over-estimated the intensity of the gamma-ray at 1.31 Mev because of insufficient resolution and the unsuspected presence of the gamma-ray at 1.66 Mev. Attributing all of the areas of the 0.84- and 1.31-Mev quanta and about one-half the area of the 1.66-Mev quantum to a hypothetical gamma-ray of energy about 1.45 Mev, and applying all corrections for that energy, an intensity about equal to that of the 2.90-Mev quantum is obtained, thus offering a possible explanation for previous interpretations.

ACKNOWLEDGMENTS

The interest in this problem of Professor H. A. Wilson, Professor T. W. Bonner,\textsuperscript{*} and Dr. W. E. Bennett, all of the Rice Institute, was deeply appreciated. The generous advices of Mr. Bob E. Watt\textsuperscript{*} in connection with the electronics of this problem are gratefully acknowledged as well as the invaluable assistance of Mr. J. F. van der Henst and Mr. P. devVries, instrument makers at the Rice Institute.

\textsuperscript{11} J. L. Lawson, Phys. Rev. 55, 131 (1939).
\textsuperscript{12} R. Wilkins, Phys. Rev. 66, 365 (1941).
\textsuperscript{*} Now at Massachusetts Institute of Technology.
Gamma-Rays from $^{56}$Sc

C. E. Mandeville

THE radioactive isotopes formed by the reaction Ca + deuterons have been investigated extensively, and the particles emitted by them have been studied in detail. Walker1 has ascribed with certainty a half-period of 44 ± 1 hr. to Sc45, and his absorption experiments have indicated that Sc45 emits two β-ray spectra, one intense and of maximum energy 0.50 Mev, the other weak and of maximum energy 1.4 ± 0.1 Mev. He reported also a γ-ray of energy 0.9 ± 0.1 Mev which appeared to be related to the two β-ray spectra. More recently, G. P. Smith4 has examined the β-ray spectrum of Sc45 by means of a spectrometer and has found one continuous distribution of maximum energy 0.610 ± 0.004 Mev. No conversion electrons arising from the γ-ray reported by Walker1 were observed nor was there any evidence of the weak disintegration electron distribution of maximum energy 1.4 ± 0.1 Mev.

Sc45 has been produced by Ca + deuterons and a further study made of its gamma-radiation. Compton recoils of the γ-rays from Sc45 have been observed with a γ-ray spectrograph which has been previously described.5 The momentum distribution of the recoil electrons is given in Fig. 1. By comparison with earlier results,6 it is seen that the γ-rays are monochromatic. Curve A was obtained on receipt of the radioactive sample and about 5 days after bombardment. Curve B was obtained 103.2 hr. after curve A, and curve C 175.5 hr. after curve A. The peaks of curves A, B, and C are in the ratio 134/27.0/8.5 to one another, and the half-life calculated from the ratios is 44 ± 1.5 hr. It is to be noted that the shape of the curve remains unchanged with time. This suggests that only one half-period is present. The γ-rays from Ca isotopes of long half-lives formed by Ca + deuterons were not present in sufficient intensity to be measured by the spectrograph. The counting rate of the G-M counters of the spectrograph was checked throughout the time of the experiment with a radium source and was found to vary by an amount less than the statistical probable error of the points on the curve of Fig. 1.

The end point of the Compton electron spectrum of Fig. 1 corresponds to a γ-ray energy of 1.35 ± 0.03 Mev. It is probable, therefore, that one mode of disintegration of Sc45 would consist in the emission of a negative electron spectrum of maximum energy 0.640 Mev followed by a γ-ray of quantum energy 1.35 ± 0.03 Mev, a more precise value than that of Walker's absorption method. In addition to information which this result gives with regard to the disintegration energy of Sc45, an excitation level in the 105 residual nucleus is established at 1.35 ± 0.03 Mev. Pollard4 has reported a level at 1.1 Mev in the Ti44 nucleus. The absence of the electrons of a converted γ-ray in the case of Smith's experiment might be attributed to a low internal conversion coefficient arising from the energy of the γ-ray and a small spin difference between the level at 1.35 Mev and the ground state of Ti44. The presence of this γ-ray indicates that the existence of the weak β-ray spectrum of high maximum energy reported by Walker1 is possible and of maximum energy about 1.99 Mev.

It is a pleasure to thank Professor A. L. Hughes and the cyclotron group of Washington University, St. Louis, Missouri, for the preparation of the radioactive material. Their effective cooperation made possible this work. Experiments of a similar nature are in progress.

1 H. Walker, Phys. Rev. 57, 163 (1940).
4 G. P. Smith, Phys. Rev. 61, 575 (1942).
Gamma-Rays from As$^{76}$

C. E. Mandeville

Reprinted from The Physical Review, Vol. 53, Nos. 3 and 4, pp. 91-95, February 1 and 15, 1938
Gamma-Rays from As\textsuperscript{76}

C. E. Mandeville
The Rice Institute, Houston, Texas
(Received December 16, 1942)

The recoil electron spectrum of the gamma-rays from As\textsuperscript{76} has been examined in a magnetic spectrograph. The spectrum was found to be composed of two electron groups corresponding to quantum energies of 0.83±0.02 and 1.94±0.04 Mev, the intensity ratio being 3.8:1. These results suggest excitation levels at 0.8 Mev and 2.8 Mev in the Se\textsuperscript{76} residual nucleus. No contributions to the spectrum of gamma-rays of energy greater than 1.94 Mev were observable.

INTRODUCTION

The nuclear radiation of As\textsuperscript{76} has been the subject of a number of recent experiments,\textsuperscript{1-5} and numerous conjectures have been made as to the energy levels of the Se\textsuperscript{76} residual nucleus resulting from beta-decay by As\textsuperscript{76}. A gamma-ray spectrograph\textsuperscript{6} has been employed in examining the energies and relative intensities of the gamma-rays arising from the de-excitation of Se\textsuperscript{76}.

PROCEDURE AND RESULTS

As\textsubscript{2}O\textsubscript{3} of chemical purity 99.95 percent was activated by slow neutrons, the reaction being As\textsuperscript{75}−n−γ. As\textsuperscript{75} is the only stable isotope of arsenic. Of the known impurities in the chemically pure As\textsubscript{2}O\textsubscript{3}, none can form a radioactive isotope when irradiated by neutrons with a half-period which differs from that of As\textsuperscript{76} by less than a factor of two. The gamma-ray activity of the irradiated As\textsubscript{2}O\textsubscript{3} was noted from time to time by means of an electroscope while the momentum distribution of the Compton recoils of the gamma-rays was being observed repeatedly in the gamma-ray spectrograph. The decay curve was followed for about 100 hours, and the activity was observed to decay with a half-life of 26.9±0.3 hr. in agreement with previously determined values\textsuperscript{1-3} running from 26 to 27 hr. The decay as observed in the electroscope is plotted in Fig. 1. Before being placed in the spectrograph, the As\textsubscript{2}O\textsubscript{3} was compressed into small cylindrical pellets so as to obtain a considerable concentration of activity, the effective width of the source remaining small.

A typical curve of the momentum distribution of the Compton secondaries of the gamma-rays from As\textsuperscript{76} is given in Fig. 2. It is there apparent that the spectrum has two strong components. The end points of the electron groups correspond to gamma-ray energies of 0.83±0.02 Mev and 1.94±0.04 Mev, respectively. The ratio of the intensity of the gamma-ray at 0.83 Mev to that of the harder one is about 3.8:1. This momentum distribution was obtained at a number of different times over the 100-hr. period in which the gamma-ray activity was likewise being observed in the electroscope as previously mentioned. The shape of the curve was found to remain unchanged with time, suggesting the presence of only one half-life, in agreement with the decay curve of the electroscope. Moreover, ordinates corresponding to the same \(H_p\) value were observed to decrease in magnitude in accordance with a half-period of 27±1.0 hr., associating the gamma-rays with the decay of As\textsuperscript{76} with certainty. A marked advantage of this method over the cloud-chamber technique when sources of sufficient strength are available is that a curve such as that of Fig. 2 may be completed in 3 or 4 hr. with high statistical accuracy whereas cloud-chamber methods require a much longer period.

DISCUSSION OF RESULTS

Harteeck, Knauer, and Schaeffer\textsuperscript{1} have reported gamma-rays at 1.50, 2.15, and 3.1 Mev using
the method of cloud-chamber pairs. Mitchell, Langer, and McDaniel have reported a maximum gamma-ray energy of 2.05 Mev as a result of absorption experiments. It is, of course, not surprising that the intense gamma-ray at 0.83 Mev was not observed in the two foregoing experiments, since its energy is not sufficient to produce the rest masses of a positron-electron pair, and it is well known that absorption methods give only the value of the energy of the

to the 3-Mev radiation observed by Hartke, Knauer, and Schaeffer.

It is to be noted that the level arrangement of Fig. 3 agrees in a qualitative sense with the \( \beta - \gamma \) and \( \gamma - \gamma \) coincidence experiments of Norling and of Mitchell, Langer, and McDaniel in that \( \gamma_a \) is associated with the beta-ray spectrum of high maximum energy and two quanta are emitted per disintegration in cascade with the beta-ray spectrum of low maximum energy. The level diagram also eliminates the association of \( \gamma_c \) with a very soft beta-ray spectrum, in agreement with the findings of Schaeffer and Hartke.

The maximum energies of the two beta-ray spectra have been tentatively assumed to be 1.0 and 3.0 Mev; these are means of the various observed and extrapolated values which have been previously reported. Any change in the assumed values would of course result in only a slight readjustment in the level diagram. The suggested arrangement of levels and the relative intensities of \( \gamma_a \) and \( \gamma_b \) are in approximate agreement with the value 3.5 : 1 given by Weil for the ratio of the intensity of the beta-ray distribution of maximum energy about 3 Mev to the intensity of the less probable distribution of lower maximum energy.

**ACKNOWLEDGMENTS**

The author wishes to express appreciation for the preparation of the radioactive As by

hardest gamma-ray present with any accuracy. No gamma-rays were observable in the neighborhood of 3 Mev. Statistical accuracy was very poor in that region, however, so that the possibility of the presence of radiation of low intensity at about 3 Mev is not excluded by this experiment. The quantum energy and intensity of the gamma-ray at 0.83 Mev, coupled with the results of previous experiments, suggest immediately the level diagram for Se given in Fig. 3. \( \gamma_a \) and \( \gamma_b \) are there given the values reported in this experiment, and \( \gamma_c \) is suggested as corresponding

![Fig. 1. Gamma-ray activity of AsO_4 irradiated by slow neutrons. The half-life taken from the slope of this curve is 26.9 ± 0.3 hr. The activity is therefore ascribed to As^{66} (T = 27 hr.).](image1)

![Fig. 2. Momentum distribution of the Compton recoils of the gamma-rays from As^{66}. The decay of the ordinates of this curve in the spectrograph was found to correspond to a half-life of 27 ± 1.0 hr.](image2)
Professor A. L. Hughes and the cyclotron group of Washington University, St. Louis, Missouri.

*Note added in proof:* This experiment has been recently repeated. Cacodylic acid (Kahlbaum) in the form of an aqueous solution has been irradiated by slow neutrons, the Washington University cyclotron again being the neutron source. H₂S was passed into the solution, precipitating the activated As ions as a sulfide. AsCl₃ and HCl had been previously added.

The results were essentially the same, γ₄ and γ₅ again being present in about the same relative intensities. A better value of γ₅ appears, however, to be 2.00±0.04 Mev. Although the source was stronger and more highly concentrated, statistical uncertainty was still rather large in the neighborhood of 3 Mev, thus preventing any conclusive statement with regard to presence or absence of γ₆. Had γ₆ been present with an intensity less than 20 percent of that of γ₅, it would have very probably escaped detection.