Energy distribution and stability of electrons in electric fields

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Intensities of γ rays, studied by means of their Compton secondaries

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Methods for investigating the γ rays from active isotopes are discussed. A method is described which permits the study of very faint samples. It is possible by this method to obtain information about the intensities as well as the energies of the γ rays. Such investigations necessitate knowledge of the efficiency curve for a secondary-electron radiator. With the aid of the known term schemes for Na24, Mn58 and Cf25 an efficiency curve for copper is constructed.

INTRODUCTION

In order to be able to establish a complete term scheme for a radioactive disintegration, it is usually necessary to determine the energies as well as the intensities of the β and γ components of the radiation. If the β spectrum has several components, these may often be separated by constructing the corresponding Fermi diagram. Such a Fermi analysis will, however, meet with great difficulties, if the upper limits of the different β components lie close together or if the components of lower energy have much lower intensities than the others. It is, in such cases, often necessary to determine in some way the difference in energy between the different β components, which is obtained, as is well known, in the form of γ radiation.

It sometimes occurs that the β transition from the active isotope direct to the ground state of the accompanying isotope is so strictly forbidden that it is absent. The ground state is in this case attained by the emission of one or several γ quanta after the β spectrum. Several of the lowest excited levels in the final nucleus may thus be missed, if the γ radiation in the disintegration is not studied.

Likewise, the probability of transitions between the excited levels may often be determined by the study of the relation between the β intensities; intensity investigations on the γ radiation must sometimes also be resorted to.
METHODS FOR INVESTIGATING $\gamma$ RADIATION

A number of methods are available for such investigations. The absorption method is probably that hitherto most employed. Its applicability is, however, limited to the occasions when there are only one or a few $\gamma$ lines. The method yields good results only if very favourable geometrical conditions are provided (large distance between sample and Geiger-Müller tube, well-canalized radiation path, etc.), together with protection against dispersed radiation. Several $\gamma$ lines, occurring simultaneously, can be satisfactorily separated only if their energies differ considerably. The other methods tried include the application of the nuclear photo-effect in D and Be, when the energy of the neutrons generated is studied. Only $\gamma$ radiation with higher energy than the threshold value for the reaction in question (2.18 and 1.62 MeV respectively) can be investigated in this way (Goldhaber, Klaiber & Scharff-Goldhaber 1944). The pair formation for $\gamma$ radiation $> 2$ mev may also be used in $\gamma$ energy determinations, though this method is rather laborious (Krugel & Ogle 1945). Coincidence investigations ($\beta$- $\gamma$ and $\gamma$- $\gamma$ coincidences) frequently yield valuable information, provided that the efficiency curves of the $\beta$ and $\gamma$ tubes as functions of the energy are well known. The last-named method is especially suited to complement the methods for the study of $\gamma$ radiation, which will be reviewed in the following account.

THE PHOTO-COMPTON METHOD

The most successful method at present for the investigation of $\gamma$ radiation is the study of the secondary electrons emitted by the photo- and Compton effects in a suitable secondary radiator. A frequent procedure is to place a thin lead or aluminium foil ($\sim$ 0.1 mm.) in a Wilson chamber at so large a distance from the sample that the direction of the $\gamma$ radiation relative to the emitted photo- or Compton electrons can be regarded as known within certain limits (Richardson & Kurie 1936). One advantage of this arrangement is that no mixing need occur between photo- and Compton electrons on the one hand and $\beta$ particles from the continuous spectrum of the active isotope on the other, since only the electrons emanating from the foil are measured. The disadvantage of the method, however, is that it has a comparatively low 'light intensity', owing to the large distance between the sample and the secondary radiator.

If the sample is placed in contact with the secondary radiator, this has to be so thick that the continuous $\beta$ spectrum is absorbed in the radiator. Combined with the $\beta$ spectrograph, this technique has been employed by Curran, Dee & Strothers (1940), Mandeville (1942), Deutsch, Elliott & Evans (1944), and the present author. Curran et al. and Mandeville have used largely the same technique: the sample is placed behind an obliquely placed, extended aluminium plate, which serves as a Compton radiator in a semicircular spectrograph. The secondary electrons are registered with the aid of the three Geiger-Müller tubes placed in a row, joined together in coincidence-coupling. The spectrograph is directly connected with the Geiger-Müller tubes so that the same pressure prevails throughout ($\sim$ 100 mm.). The lowest $\gamma$ energies capable of investigation are reported by Mandeville to be 0.5 MeV. Each $\gamma$ energy gives, according
to Mandeville, a typically peaked, symmetrical Compton distribution. The intensities of the different γ components are obtained by dividing the areas of the Compton distributions by the corresponding Compton coefficients and the maximum ranges of the Compton electrons.

An essentially different technique has been developed by Deutsch et al. (1944) and the present author. The sample is pressed into a small, cylindrical radiator (ϕ = 8 mm.), whose walls are thick enough to absorb the continuous spectrum. Copper is a suitable material to limit the size of the radiator, for it has a high density but an atomic number low enough to give almost exclusively Compton effect at energies > 0.5 MeV. If the outside of this radiator is covered with a thin lead foil, photo-electrons from the thin lead foil are obtained in addition to the Compton electrons. If the secondary-electron distribution, obtained in experiments with and without lead foil, is subtracted, there remain the photo-lines from lead. Very accurate energy determinations of the γ radiation may be attained in this way, as the peak of a line can be more accurately measured than the sloping edge of a Compton distribution.

The radiation from the secondary radiator is studied in a lens β spectrograph of high light intensity (in course of publication). It has proved possible, by adjusting slits and diaphragm to a resolving power of 5 % (defined from the half-breadth value of a β line), to measure accurately the energy as well as the intensity for samples whose γ radiations are no higher than ~ 1 μC Ra-γ equivalence/γ line. The Geiger-Müller tube in the β lens spectrograph will, for obvious reasons, be so far from the sample that the γ radiation from the latter will not considerably influence the zero effect of the tube. A special arrangement for coincidence-coupled β tubes is also unnecessary. It is difficult to fix a limit for the lowest γ energies susceptible of study by this method. This depends mainly on the thickness of the copper radiator necessary for the absorption of the β spectrum. Hitherto, γ energies of < 100 keV (Slåtis 1946) have been successfully investigated. Apart from the γ absorption in the radiator, however, there is nothing to prevent the study of still lower energies.

The photo- and Compton methods seem to complement each other excellently. The photo-method is superior for γ energies of, for example, 800 keV and below, owing to the fact that the photo-lines obtained within this range of energy lie so high above the corresponding Compton distributions that they can easily be subtracted from the total curve.

As the energy becomes higher, however, the Compton method will be more and more applicable. It is, of course, always possible to separate satisfactorily the photo-line from the corresponding Compton edge, if the resolving power of the spectrograph is sufficiently high (which involves a reduced intensity). It proves difficult, however, at the resolving power used by the present author (5 %), to obtain clearly observable photo-lines for large γ energies. These often reveal themselves as an inconsiderable "terracing" of the Compton edge. Obviously the intensity of such a photo-line is particularly uncertain. This does not, however, apply to the Compton distribution. The continuous-energy distribution of the latter makes it possible to base the intensity measurements on a number of points of measurement, all of equal value. The rather
characteristic form that the Compton distributions are proved to possess by closer experimental study further increases the possibility of obtaining good $\gamma$ intensity determinations based on this effect.

The problem of how to calculate, from photo-lines, the corresponding $\gamma$ line intensities, has earlier been dealt with in a convincing manner by Deutsch et al. (1944) and will therefore not be discussed here. The remaining part of this paper will instead deal with determinations of the $\gamma$ intensity from the corresponding Compton distributions.

**The efficiency curve for a copper radiator**

The number of Compton electrons (i.e. the area below the Compton distribution) emanating from the radiator and registered in the spectrograph, is a function of the energy of the $\gamma$ line. This is due to the facts that the Compton coefficient varies with the energy and that the absorption of the liberated secondary electrons also varies with the energy. These two effects act in opposing senses, since the Compton absorption coefficient decreases as the energy increases, whereas the range of the secondary electrons naturally increases as the $\beta$ energy increases. This latter functional process is steeper than the former, which implies that the 'efficiency' of the radiator for different $\gamma$ energies is an ascending function. It is evidently necessary to know this function, in order to calculate the intensity of the $\gamma$ line from the known area of the Compton distribution.

![Figure 1. $\gamma$ spectrum of Na$^{24}$](image)

Possible though it be to treat this problem theoretically, the following empirical procedure is certainly simpler and possibly more reliable. The relations are studied between the areas under the Compton distributions originating from different $\gamma$ lines, the relative intensities of which may be considered as known from other data in the term scheme of the disintegration.

At present, unfortunately, but few cases are known of disintegrations where the term scheme is completely clear. These include a still lower number for which the intensity data are also determined. As a basis for the efficiency curve for copper as
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a secondary radiator, the disintegrations of the active isotopes Na\textsuperscript{24}, Mn\textsuperscript{56} and Cl\textsuperscript{38} have been chosen.

Na\textsuperscript{24} has a simple β spectrum, and the two γ lines (1.38 and 2.76 MeV) must be emitted in cascade after the β spectrum (Elliot, Deutsch & Roberts 1943; Siegbahn 1946b). Accordingly, the intensities of the two γ lines are in the proportion 1 : 1. Figure 1 shows the appearance of the Compton secondaries from copper for these two γ lines. The curve may be resolved into two components with largely similar form. It is intriguing to note that each curve is horizontal over a large energy range in the central part. The ratio of the areas is 2.65.

\[ \begin{align*}
Mn\textsuperscript{56} & \rightarrow \beta_1 \rightarrow \gamma_1 \\
 & \rightarrow \beta_2 \rightarrow \gamma_2 \\
 & \rightarrow \beta_3 \rightarrow \gamma_3
\end{align*} \]

\[ \begin{align*}
Fe\textsuperscript{56} & \rightarrow \gamma_1 \\
 & \rightarrow \gamma_2 \\
 & \rightarrow \gamma_3
\end{align*} \]

**Figure 2.** Term scheme for the disintegration of Mn\textsuperscript{56}.

The disintegration of Mn\textsuperscript{56} is considerably more complicated (Siegbahn 1946a). It is illustrated by the term scheme in figure 2. Knowing the intensities of the various β transitions, one may calculate the corresponding data for the γ transitions. The ratio of \( I_{\beta_1} \) and \( I_{\beta_2} \) is a little uncertain (approx. 2 : 3), whereas \( I_{\beta_1} + I_{\beta_2} : I_{\beta_3} \) may be given with greater accuracy as 1 : 00. According to the term scheme, the sum of \( I_{\gamma_1} (E_{\gamma_1} = 1.77 \text{ MeV}) \) and \( I_{\gamma_2} (E_{\gamma_2} = 2.06 \text{ MeV}) \) must then be 50% of \( I_{\gamma_3} (E_{\gamma_3} = 0.822 \text{ MeV}) \). The mean of the energies of \( \gamma_1 \) and \( \gamma_2 \) may then reasonably be placed at 1.87 MeV, considering that \( \gamma_1 \) is stronger than \( \gamma_2 \). Figure 3 shows the recording of the Compton secondaries from copper for the γ radiation. The different components have, according to the figure, approximately the same characteristic forms as in the case of Na\textsuperscript{24}. The ratio of the sum of Compton distributions for \( \gamma_1 \) and \( \gamma_2 \) to that of \( \gamma_3 \) is 1.36. Thus, the efficiency of the copper radiator, considering that \( I_{\gamma_1} + I_{\gamma_2} = 50\% \) of \( I_{\gamma_3} \) is 2.72 times greater at 1.87 MeV than at 0.822 MeV.
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Cl$^{38}$ also has a rather complex disintegration, which is clear from the term scheme in figure 4 (Hole & Siegbahn 1946). The proportions of the intensities of $\beta_1$, $\beta_2$ and $\beta_3$ are (from the Fermi analysis of the $\beta$ spectrum) $36:11:53$. Hence, the conclusion may be drawn that the ratio of $I_{\gamma_1}$ (1·60 MeV) and $I_{\gamma_2}$ (2·15 MeV) should be 43:57.

![Figure 3. $\gamma$ spectrum of Mn$^{56}$](image)

The Compton recording of the two $\gamma$ components is shown in figure 5, where the characteristic energy distribution of the secondary electrons is again to be seen. The ratio of the areas of the two components is $60:120$. The efficiency values of the copper radiator at 2·12 and 1·65 MeV are accordingly in the ratio $120/57:60/43 = 1·50$.

The efficiency curve of the copper radiator has been constructed in figure 6 from the above results. This has been done in the following way. The efficiency at the energy 1·38 MeV has been arbitrarily taken as unity. An additional point of the curve at 2·76 MeV may at once be obtained from Na$^{24}$. Further, the ratio of the efficiency values
at 1.85 and 0.822 MeV (from Mn$^{56}$) is known to be 2.72. Since the curve may be supposed to have an approximately monotonic course, there is no difficulty in adjusting the two points from Mn$^{56}$ so that an even curve may be drawn through all four points.

![Graph of γ spectrum of Cl$^{38}$](image)

**Figure 5.** γ spectrum of Cl$^{38}$.

![Graph of efficiency curve](image)

**Figure 6.** The efficiency curve for a Cu radiator.

A very satisfactory check on the efficiency curve thus obtained is provided by the fact that the two points obtained from Cl$^{38}$ also lie on the curve.

The accuracy of intensity determinations based on this method may be estimated as 10%, possibly somewhat higher. About the same value is given for the photo-method
by Deutsch et al. (1944). The largest error lies in the sometimes rather difficult separation of the $\gamma$ components. It is, however, helpful to know that each component seems generally to have the characteristic form shown by the above examples. The geometrical form of the radiator does probably not affect, to any considerable extent, this energy distribution, although this matter calls for somewhat closer study. Nevertheless, the efficiency of the radiator as a function of the energy appears to be inappreciably influenced by small changes in the form of the energy distributions of the components.

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