

The Electron Spectra Produced by a Co^{60} Source in Water*

EVANS HAYWARD

National Bureau of Standards, Washington, D. C.

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The spectra of secondary electrons produced by a Co^{60} gamma-ray source have been measured at distances of 10, 20, 41.6, 81.6, 121.6, and 161.6 cm in a large tank of water. The pulse-height distribution representing the energy lost in an anthracene crystal was determined for each separation of detector and source. The shape of the spectrum was found to change appreciably with distance. The results agree remarkably well with theoretical predictions.

INTRODUCTION

AS gamma-radiation penetrates matter, it interacts with it through the photoelectric effect, Compton scattering, and pair production, the predominance of one effect over the others depending on the energy of the quanta and the atomic number of the material. Various calculations¹ have been made that give the general characteristics of the radiation such as intensity, energy, and angular distribution as a function of distance from the source, energy of incident radiation, and atomic number of the medium. Experimental determination of these quantities is difficult, since they should be measured in an infinite medium using detectors that do not appreciably disturb any of the quantities being observed. A measurement of radiation intensity as a function of distance from the source has recently been determined by White² for the Co^{60} radiation in water. It is now possible, since the development of scintillation spectroscopy, to measure with low resolution, the energy spectrum of the secondary electrons produced in an infinite medium as a function of distance from the source.

Since anthracene has an atomic number and density close to those of water, its absorption coefficient is practically the same as that of water and an anthracene crystal may be used to represent an equal mass of water. Thus, the distribution of pulse heights observed with an anthracene crystal would correspond to the energy distribution of the electrons produced in an equal mass of water occupying the same position, provided that none of the auxiliary measuring equipment distorts the spectrum.

EXPERIMENTAL DETAILS

The experimental arrangement is shown in Fig. 1. The experiment was performed in a large (12 ft \times 12 ft \times 25 ft) tank of water so that there would be no boundary effects. The counter consisted of an anthracene crystal, Lucite light pipe, RCA 5819 photomultiplier tube, and cathode follower all enclosed in an

aluminum and Lucite can; the cables came out of the water through a piece of copper pipe. The counter was designed to have its active volume surrounded by water-equivalent material, so that it would be separated from discontinuities such as the vacuum within the photomultiplier tube. A Lucite light pipe one inch in length separated the crystal from the photomultiplier tube and a Lucite cap fitted over the crystal, light pipe, and the top of the 5819 to protect them from the water. A thin piece of aluminum foil served as a reflector, and was introduced between the crystal and the Lucite cap. Both the source and the counter were suspended near the center of the water tank from a wooden rack.

The counter was designed to measure the energy of any electron that was produced in and totally absorbed by the anthracene crystal. Electrons created outside of, but scattered into the crystal, and those created inside, but ending outside of the crystal, produce a heightening at the low energy end and a lowering of the high energy end of the spectrum. A study of the shape of the

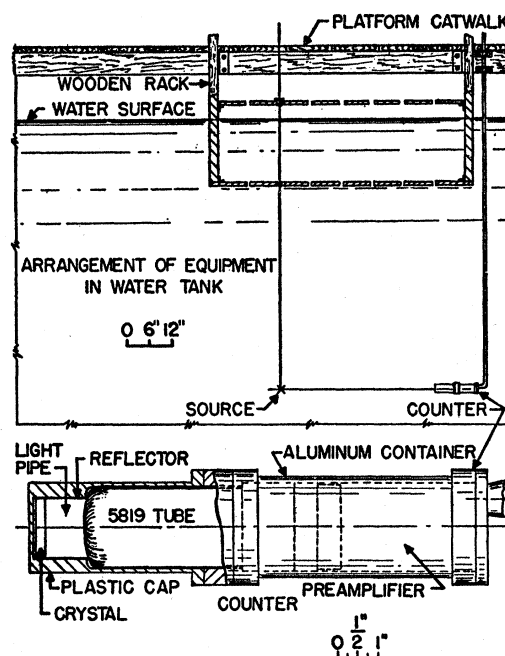


FIG. 1. The experimental arrangement.

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¹ L. V. Spencer and U. Fano, J. Research Natl. Bur. Standards 46, 446 (1951); Phys. Rev. 81, 464 (1951); L. V. Spencer and F. Stinson, Phys. Rev. 85, 662 (1952).

² Gladys R. White, Phys. Rev. 80, 154 (1950).

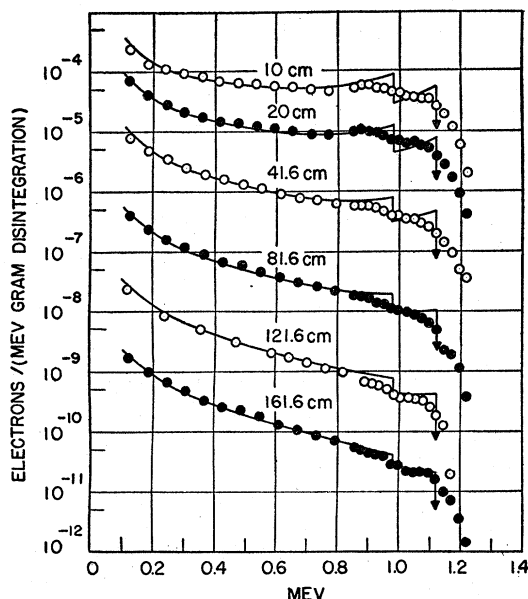


FIG. 2. The differential spectra of the electrons produced by a Co^{60} source as a function of the distance in water. The solid curves were calculated according to the method of Spencer and Fano (see reference 1).

spectrum as a function of crystal thickness showed the magnitude of this effect to be negligible. Checks were also made to be sure that the shape of the spectrum was sensitive neither to light pipe length, nor to the presence of a second photomultiplier tube close to the crystal.

The pulse from the preamplifier was fed into a linear amplifier, and then into a single channel differential pulse-height analyzer. The pulse-height analyzer observed the spectrum through a $1\frac{1}{2}$ volt window (corresponding to ~ 18 kev) which was moved between 10 and 100 volts. The linearity and zero of the discriminator were checked with a pulse generator.

The resolution of the instrument was determined from the width of the internal conversion line of Cs^{137} (632 kev). A very weak Cs^{137} source was prepared, covered with a Formvar film and placed on top of the crystal and inside of the reflector, so that the beta-spectrum and the internal conversion electrons were observed. The pulse-height distribution resulting from the internal conversion line is Gaussian with a half-width of 110 kev.

Six Co^{60} sources ranging from 10^6 to 10^{11} disintegrations per second were used at six different separations between source and detector. It was necessary to use a different source for each separation, in order to have low enough counting rates to avoid "pile-up" from the very large number of low energy electrons characteristic of these spectra. The relative intensities of these sources have been measured in pairs and compared to a standard; their specific activities are known within ± 6 percent.

When a slowly and smoothly varying spectrum such as this, is measured with a low resolution device, the shape of the spectrum is changed very little except at points where discontinuities exist. For example, the Compton spectrum that is generated by a monochromatic gamma-ray falls sharply to zero after a pronounced peak at the maximum possible energy. This peak, when measured with a scintillation spectrometer, is smeared out, but the energy corresponding to the maximum electron energy may be taken with fair accuracy as the point of maximum slope.³ In the early stages of the experiment Cs^{137} , as well as Co^{60} gamma-ray sources, were used to calibrate the instrument. Later it was found that the spectrum measured under actual operating conditions in the water tank fell off sharply at the point corresponding to the end of the Co^{60} spectrum and thus a separate calibration was eliminated.

RESULTS

The electron spectrum produced by the 1.17- and 1.33-Mev Co^{60} gamma-rays has been measured at 10, 20, 41.6, 81.6, 121.6, and 161.6 cm from the source. Figure 2 shows the six spectra plotted on semi-logarithmic paper.

The ordinates are given as the number of electrons per Mev interval, per disintegration of the source, and per gram of anthracene. In order to express the data in these units, it is necessary to know not only the counting rate but also the disintegration rate of the source and the window width of the discriminator. The standard error for the absolute intensities is ± 10 percent, due mostly to uncertainties in the determination of the latter two quantities. The energy scale of the abscissa was obtained by making a linear plot of the data and taking the two points of inflection at the end of the spectrum as corresponding to 0.96 and 1.12 Mev, the maximum energy Compton electrons that can result from the 1.17- and 1.33-Mev gamma-rays. This calibration is good to about ± 1.5 percent. The standard deviations based on the number of counts are all less than ± 5 percent and almost all less than ± 3 percent. The background was negligible, since the large mass of water provides an excellent shield to stray radiation.

The solid curves in Fig. 2 were calculated according to the methods outlined in reference 1 and were very kindly supplied by Dr. L. V. Spencer. It is clear that the experimental data have the same general characteristics as the theory predicts; the measured spectrum changes with penetration in the same way as the theoretical one and the absolute intensities agree very well.

At 10 cm the high energy end of the spectrum is quite intense, and the two peaks corresponding to the two gamma-rays are obvious. At greater distances, the energy loss becomes more and more concentrated in

³ P. R. Bell and J. M. Cassidy, Phys. Rev. **77**, 409 (1950).

the lower energy electrons and the rate at which the spectrum changes becomes less and less. In fact, at distances of a meter or more, the changes in the shape of the spectrum are too small to be measured with this low resolution spectrometer.

White² has already made some measurements in a similar experiment, using shielded ionization chambers, and found that the spectrum is still changing as far out from the source as 135 cm. These data do not, however, contradict the results of the present experiment since the ionization chambers are sensitive mostly to very soft radiation, so soft in fact as to have had no effect in this experiment. Furthermore, the spectra of photons calculated by Spencer and Fano¹ show the

features of both experiments. The calculated spectra show a peak below 100 kev the height of which, relative to the high energy portion of the spectrum, is still changing at large distances; this component is primarily the one measured by White.² On the other hand, the shape of the calculated spectra at high energies change very slowly with distance, too slowly for any variation to be observed with the spectrometer used in the present experiment.

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The Radial Distribution Function in Liquid Helium*

P. J. PRICE

Department of Chemistry, Duke University, Durham, North Carolina

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It is pointed out that the Ornstein-Zernike-Gibbs formula, which is commonly used to connect the intensity of coherent scattering of radiation in a liquid with the thermodynamic functions, is not valid for liquid helium. Alternative formulas involving the radial distribution function are discussed.

IN the coherent scattering of radiation by a monatomic liquid, the scattered intensity is proportional to¹

$$1+n \int [g(r)-1] e^{i(\mathbf{k}_1-\mathbf{k}_2) \cdot \mathbf{r}} d^3\mathbf{r}, \quad (1)$$

where n is the number density, $g(r)$ the radial distribution function, and \mathbf{k}_1 and \mathbf{k}_2 the incident and scattered wave vectors. Consequently, for large wavelengths the scattering cross section is multiplied by the factor

$$S(T) \equiv 1+n \int_a^\infty (g-1) 4\pi r^2 dr, \quad (2)$$

and the scattered intensity can be related to the thermodynamic magnitudes of the liquid by the formula

$$S = nkT\chi_T, \quad (3)$$

where χ_T is the isothermal compressibility. This formula (3) is valid for "classical" conditions, but has recently been applied to the analysis of scattering in liquid helium.²

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¹ A general reference on the results (1)-(5) is: J. de Boer, Reports on Progress in Physics **12**, 305 (1949), §10.

² Goldstein, Sommers, King, and Hoffman, Proceedings of the International Conference on Low Temperature Physics, Oxford, 1951, p. 88; see L. Goldstein, Phys. Rev. **84**, 466 (1951), Fig. 1.

It is the present purpose to point out that this application to a *quantum* liquid is incorrect. To see this, we break down (3) into the two equations from which it derives. Consider a small fixed cell of volume v in the liquid, which is supposed homogeneous, and define the function $f(\mathbf{r})$ such that f is unity when \mathbf{r} ends in the cell and zero otherwise; and hence the function $F = \sum f(\mathbf{r}_i)$, summed over the position-vectors \mathbf{r}_i of the atoms, whose expectation is the average of the number of atoms in the cell, $\langle F \rangle = \bar{F}_{ii} = nv$. Then the fluctuation of the expectation of F , over the probability distribution of the \mathbf{r}_i , can be shown to be given by (2):

$$[\langle F^2 \rangle - \langle F \rangle^2] / \langle F \rangle = S. \quad (4)$$

This result (4) is true equally for "classical" and "quantum" conditions [as is (1)], and depends on the assumptions that (i) there is a radius a beyond which $g(r)$ tends to its (normalized) limit of unity, and such that $\int_a^\infty (g-1) 4\pi r^2 dr$ is negligible; and (ii) v is large compared with $4\pi a^3/3$ and small compared with the volume of the whole liquid. For a quantum liquid the left-hand side of (4) must remain finite even at absolute zero, owing to the zero-point motion of the atoms, since the probability distribution of the atoms is essentially positive. This shows that (3) cannot then be true, since for a quantum liquid $n\chi_T$ remains finite, and hence $nkT\chi_T$ becomes zero, when $T \rightarrow 0$. Another case to which the same argument applies is that of the ideal Fermi gas. To arrive at (3) we would have to combine (4) with