The solubility of He^4 in Table II is represented by $S_4 = 4.438 \times 10^{-3}\ e^{885/RT}$. Williams and Ferguson[6] obtained solubilities of 0.0101 and 0.0103 at 515 and 445°. The diffusion coefficient D is given by the right-hand side of equation (3), provided p is replaced by c, the concentration of He in silica at the inner surface of the sphere. Since $c = sp$, where s is the solubility, we have $D_4 = P_4/S_4 = 2.575 \times 10^{-7}\ T^{1/2}\ e^{-5585/RT}$ cm.^{2} sec.$^{-1}$.

A plot of log P or log D against $1/T$ is slightly concave up, as has previously been observed in this and other cases.[3-5] Such behavior might be due to a small admixture of slip-plane diffusion of lower activation energy than the main process of lattice diffusion.[5] The curvature mentioned might be partly connected with a theoretical inadequacy in the choice of the pre-exponential term even if there were a well-defined activation energy. Such an effect would be emphasized by the relatively small activation energy. The curvature may also be due to the fact that the distributed nature of the parameters defining a glass gives rise to a corresponding spectrum of activation energies. The tendency of lattice expansion to give a lower activation energy at high temperatures is probably small with quartz.

(6) G. A. Williams and J. B. Ferguson, THIS JOURNAL, **46**, 635 (1924).

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A Convenient Source of Gamma Radiation

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A simple irradiator is described which gives intense and uniform gamma radiation from Co^{60} for laboratory experiments involving objects of relatively small size.

An intense and uniform source of γ-rays capable of irradiating large numbers of small specimens was needed in a research program on the thermoluminescence of crystals. A hollow Co^{60} cylinder has solved the problem so successfully that a description of it may be of help to others. Thousands of irradiations have been carried out with this simple and inexpensive source since its development in 1949.[1,2] The γ-ray flux is uniform because of the geometrical characteristics, and it is intense because the samples to be irradiated are placed inside the source and receive radiation from all sides. The γ-radiation extending outward from the source is of sufficiently low enough intensity that safe handling and shipping may be carried out easily. An unshielded 3-curie source giving a radiation intensity of approximately 4 roentgens per hour at a distance of 1.0 meter will provide an intensity of about 6,000 roentgens per hour inside the source.

Similar cylindrical Co^{60} γ-ray sources have been prepared in other laboratories for studies in radiation chemistry[3] and to develop new applications for fission products.[4] The high activity of these other sources (300 to 1,000 curies) requires that special apparatus and techniques be used for safe preparation and handling. The smaller size of the sources described below produces a high radiation intensity per unit of radioactivity, making high γ-ray fluxes available to laboratories not possessing specialized facilities.

A hollow cylinder of cobalt metal powder was prepared by filling the space between two concentric aluminum cans. The aluminum container must be absolutely tight to prevent the escape of any trace of radioactive cobalt powder. The powder was used because it is easily available whereas the machining of cobalt metal is very difficult.[5]

A plan of the apparatus is shown in Fig. 1. The cylindrical aluminum cans were welded from standard aluminum containers used for neutron irradiations in the nuclear reactor at the Argonne National Laboratory. The outer aluminum cylinder has an outer diameter of 3.1 cm. and the inner cylinder has an inner diameter of 2.2 cm. The height is 13.5 cm. The top and bottom of the concentric cylinders are closed with a thick aluminum ring to which the two cylinders are welded after filling up the space between them with pure chemical-grade cobalt powder.

The first model of this apparatus was placed in the nuclear reactor at the Argonne National Laboratory and exposed to a neutron flux for a sufficient time to produce 0.7 curie of radioactive cobalt. Radioactive cobalt (Co^{60}) has a half-life of 5.3 years and decays with the emission of weak β-rays and 1.17 and 1.33 mev. γ-rays.

A second gamma source of the same type was irradiated at the Oak Ridge National Laboratory to produce 3 curies of radioactive cobalt.

Specimens are placed in an aluminum rack which fits in the source. This rack holds several solid pieces, 1 cm. square and a few millimeters thick, sawed from a rock or cleaved from a crystal, or it can hold 40–50 gelatine capsules containing powdered specimens. It has been used for irradiating biological material including live bumble bees and fruit flies. The 0.7-curie and 3-curie irradiators are kept in separate compartments of a lead container with walls seven inches thick. This is set in the floor of an isolated basement room. A mirror is placed at an angle of 45 degrees about 1.0 meter above the irradiators. The specimens are lowered into the irradiator and removed with a "fish pole."

The relative and absolute radiation intensities in the irradiators were determined by using the thermoluminescence of lithium fluoride crystals as dosimeters as will be described in detail in a forthcoming communication. Lithium fluoride, as well as other alkali halides, emits light on heating after an exposure to high energy radiation such as X-rays, γ-rays and α- or β-particles. This thermoluminescence is measured by recording the changes in light intensity as measured by a multiplier phototube while the temperature of the specimen is increased at a rate of about 1° per second. The resulting light intensity–time curve or the

(1) Farrington Daniels and D. F. Saunders, *Science*, **111**, 462 (1950).

(2) D. F. Saunders, Ph.D. Thesis, University of Wisconsin (1950).

(3) J. A. Ghormley and C. J. Hochanadel, *Rev. Sci. Instruments*, **22**, 473 (1951).

(4) B. Manowitz, *Nucleonics*, **9**, No. 2, 10 (1951).

(5) It has been learned that cylinders of cobalt metal can be made by Technical Fabrications Co., Cambridge, Massachusetts, and by Eldorado Mining and Refining (1944) Ltd. Ottawa, Canada.

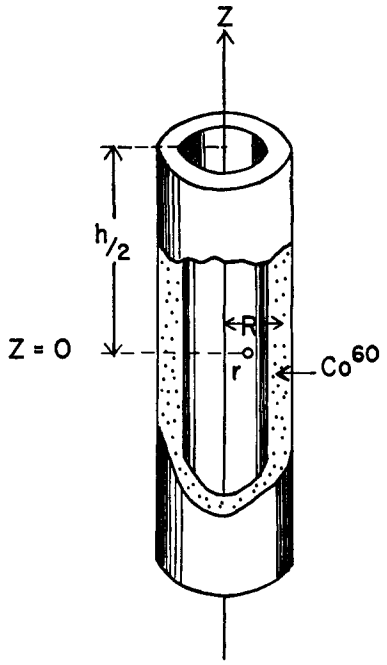

Fig. 1.—Gamma source.

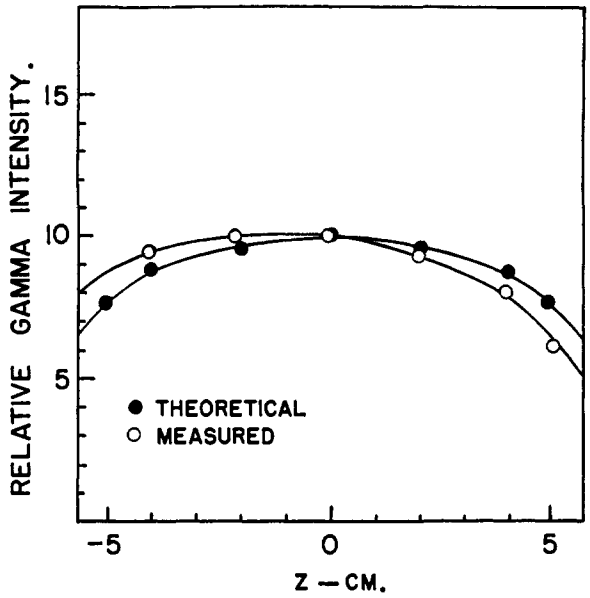

Fig. 2.—Intensity distribution along axis of source.

replotted light intensity–temperature curve (glow curve) passes through a series of maxima.

The height of the lithium fluoride glow curve maximum at 220° was used as a measure of the amount of light emitted by any particular specimen. This value was corrected to a standard weight of lithium fluoride. All the specimens used for calibration were obtained by cleaving plates 1 cm. square by 1–2 mm. thick from a large single crystal of lithium fluoride obtained from the Harshaw Chemical Co. By measuring the thermoluminescence of specimens placed in the same position within one of the irradiators as a function of time of exposure to gamma radiation, an equation was found which related the amount of thermoluminescence to the amount of γ-radiation. For very short exposures the thermoluminescence was nearly proportional to the square of the time of exposure, but became directly proportional for slightly longer exposures.

The relative radiation intensities along the length of each irradiator were determined by measuring the thermoluminescence of lithium fluoride specimens which were distributed along the axis of the source and given equal exposure times. By comparing these measurements with the curve of thermoluminescence as a function of exposure time, it was possible to construct radiation intensity distribution curves as shown in Fig. 2 for the 3-curie source. The γ-intensities are given in arbitrary units. This curve agrees quite well with relative values as calculated from geometrical considerations of the distribution of activity in the source. The differences between the curves are attributed to compaction of the cobalt powder at the bottom of the source.

In order that absolute γ-intensities in roentgens per hour might be calculated other specimens of lithium fluoride were exposed to γ-radiation outside the 0.7-curie source at a distance of 1.0 meter. The radiation intensity at this point was determined by a standardized ionization-type survey meter. The thermoluminescence produced was compared with that obtained from the specimens exposed inside the irradiators. By combining these data with the known equation for the increase of thermoluminescence with the amount of γ-radiation and the ratio of the times of irradiation in the two instances, it was possible to calculate the intensity of radiation inside the source. The values obtained were about 1,400 roentgens per hour at the center of the 0.7-curie source and about 6,000 roentgens per hour at the center of the 3-curie source.

Calculation of Radiation Intensity.—As a check on the measured radiation intensity in the 3-curie source, we have calculated the radiation intensity distribution along the axis of the source and in a plane perpendicular to the axis at the center.

In these calculations, one assumes that the annulus containing the Co^{60} is sufficiently thin so that one may use an "area" rather than a "volume" distribution of the Co^{60}. That is, the Co^{60} is assumed to be uniformly distributed over the surface of a cylinder of radius R, where R is the mean radius of the two aluminum cans, 1.35 cm. in this instance. The height, h, is approximately 12 cm., which includes only the portion containing Co^{60}.

The radiation intensity, I, in roentgens per hour produced by a point source of 1 curie of Co^{60} at a distance D cm. in dry air at 0° and 760 mm. is given by

$$I = \frac{(3.7 \times 10^{10})(3600)(1.17 \times 3.53 \times 10^{-5} + 1.33 \times 3.41 \times 10^{-5})}{4\pi D^2(6.77 \times 10^4)} = \frac{1.356 \times 10^4}{D^2} \text{ roentgens per hour}$$

Here $\frac{1}{4}\pi D^2$ is the fraction of energy emitted by the Co^{60} passing through a 1-cm.^{2} area at D cm. The absorption of 6.77×10^4 mev. is the equivalent of 1 roentgen. The absorption coefficients of 1.17 and 1.33 mev. gammas are 3.53×10^{-5} cm.$^{-1}$ and 3.41×10^{-5} cm.$^{-1}$, respectively,[6] neglecting photoelectric and pair production absorption.

If Z is the position on the cylinder axis and r the radial distance from the axis to the point at which it is desired to know the radiation intensity, then the intensity, I_s, due to surface element $R\,d\theta\,dZ^1$ located at Z^1, R and θ is

$$I_s = \frac{(N\,R\,d\theta\,dZ^1)(1.356 \times 10^4)}{D_2}$$

where

$$D^2 = (Z - Z^1)^2 + R^2 + r^2 - 2Rr\cos\theta$$

and N is the surface concentration of the source in curies per square centimeter. If we set $r = 0$ we get the radiation intensity along the axis, Ia, by integrating over θ and Z^1.

(6) R. E. Evans, *Nucleonics*, 1, No. 4, 32 (1947).

$$I_a = H\int_{h/2}^{h/2}\int_0^{2\pi}\frac{d\theta\, dZ^1}{D^2}$$

$$= 2\pi H\int_{-h/2-Z}^{h/2+Z}\frac{d(Z-Z^1)}{(Z-Z^1)^2+R^2} =$$

$$\frac{2\pi H}{R}\left[\tan^{-1}\frac{h/2-Z+}{R}\tan^{-1}\frac{h/2+Z}{R}\right]$$

where $H = NR\,(1.356 \times 10^4)$.

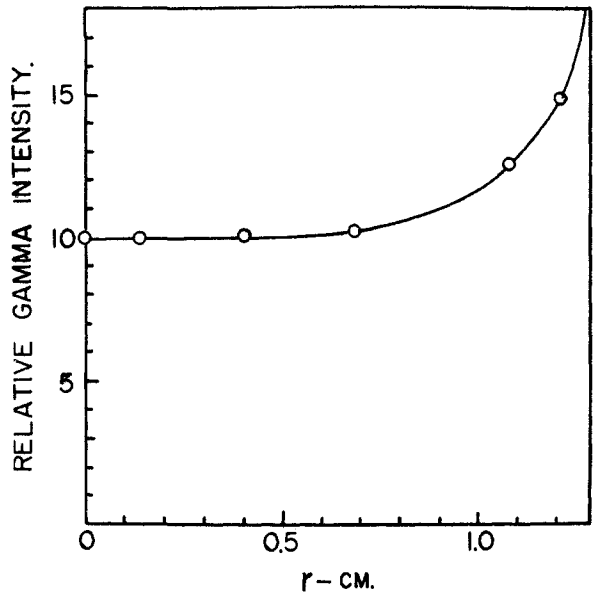

Fig. 3.—Radial intensity distribution at center of source ($Z = 0$).

For the 3-curie source, the radiation intensity at the center ($Z = 0$) is calculated to be 6750 roentgens per hour which agrees reasonably well with the value of 6,000 roentgens per hour as measured by the thermoluminescence method. The relative intensity distribution along the axis of the source is shown in Fig. 2.

The radial intensity distribution at any point is found by first integrating over θ.

$$I_r = 2NR(1.356 \times 10^4)\int_{-h/2}^{h/2}\int_0^{\pi}\frac{d\theta\, dZ^1}{a + b\cos\theta}$$

$$= 4\pi NR(1.35 \times 10^4)\int_{-h/2}^{h/2}\frac{dZ^1}{\sqrt{a^2-b^2}}$$

where $a = (Z - Z^1)^2 + R^2 + r^2$

$b = -2Rr$

The integration over Z^1 is most easily done graphically, and the result for $Z = 0$ is shown in Fig. 3. The relative uniformity of the intensity when r is less than 0.7 roentgen has been shown experimentally. A photograph of the thermoluminescence emitted by a large crystal of lithium fluoride irradiated in the source showed almost completely uniform blackening except for an increase at the edges, which was shown to be due to internal reflection. The same blackening increase at the edge was present for a crystal whose edges were cleaved off after irradiation and before photographing.

One may check the figure thus obtained for the intensity at the center by comparing the intensity measured with a survey meter at a point directly above the source with a value calculated from the formula for the intensity along the axis, corrected for the self-absorption of the Co^{60}. The measured value was 0.80 roentgen per hour while the calculated was 0.805 roentgen per hour.

Secondary electrons produced by the gammas in the cobalt and aluminum have been neglected in the above calculations. The thermoluminescence of lithium fluoride crystals wrapped tightly in heavy foil metal (cadmium) did not differ from that of unwrapped crystals given an equal exposure. It has been found that the thermoluminescence of lithium fluoride is extremely sensitive to exposure to low energy electron beams (~6 kev.). Hence, neglect of the secondary effects would seem to have some empirical justification.

During the past three years of research on the thermoluminescence of crystals these γ-irradiators have been in constant use and have given very satisfactory service.

We are particularly indebted to Dr. E. W. Rylander and to the Argonne National Laboratory for their coöperation in preparing this γ-ray source and irradiating the first source. We are indebted also to the Oak Ridge National Laboratory for irradiating the second source. This investigation was carried out with the help of a grant from the Atomic Energy Commission.

MADISON, WISCONSIN