Response of Anthracene Scintillation Crystals to Monoenergetic Soft X-Rays*

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The response of anthracene to monoenergetic x-rays in the range from 9 kev to 24 kev in a scintillation detector has been investigated. The results show that the response to short-range electrons produced within the crystal by x-rays is about the same as the response to electrons with equal energy incident on the surface of the crystal. In agreement with previous results, the specific fluorescence (dL/dx) is smaller for slow electrons than for heavy particles of the same specific energy loss (dE/dx).

I. INTRODUCTION

THE response of some organic scintillation crystals to charged particles has previously been investigated by Birks,[1] Franzen *et al.*,[2] Hopkins,[3] Cross,[4] Taylor *et al.*,[5] and King and Birks.[6] The results obtained by Taylor *et al.*[5] indicated that both anthracene and stilbene have slightly different fluorescence efficiencies for protons and alpha particles of the same specific energy loss. However, for electrons of energies below 30 kev they found a fluorescence efficiency considerably lower than that of protons and α particles of the same specific energy loss. In their experiment, radioactive sources of internal conversion electrons provided single electrons with energies from 30 kev to 600 kev. In the range from 0.5 kev to 5 kev a pulsed beam of electrons was used. No measurements were performed in the range from 5 kev to 30 kev.

The use of external electron sources and the resulting surface effects and back-diffusion of electrons in the experiments of Taylor *et al.*[5] might explain part of the difference between the fluorescence efficiency for electrons and heavy charged particles. The purpose of the present experiment, therefore, was the investigation of the response of anthracene to electrons produced inside the crystal where these effects are not present. Electrons with energies between 9 kev and 24 kev were used. Measurements with energies below 9 kev were not made since the signal pulses were not distinguishable from photomultiplier tube noise. The results show that the response of short-range electrons produced within the crystal by x-radiation is within the limits of error the same as the response to electrons with equal energy incident on the surface of the crystal. In agreement with previous results, the specific fluorescence (dL/dx) for slow electrons is smaller than that for heavy particles of the same specific energy loss (dE/dx).

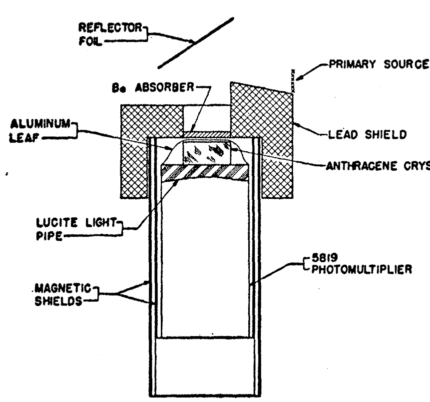

FIG. 1. Experimental arrangement for the measurement of the response of anthracene to fluorescent x-rays.

II. EXPERIMENTAL PROCEDURE

Monoenergetic photoelectrons were produced inside the anthracene crystal (2 cm×2 cm×1 cm) by incident x-radiation. X-rays in the range from 9 kev to 24 kev were obtained in two ways: (1) directly from a radioactive source decaying by K capture, and (2) from fluorescent x-radiation excited in suitable metal foil "reflectors" by radiation from a primary x-ray source following a method described by Insch.[7] For the first method we used the K x-rays of gallium and indium which are emitted after the K capture of Ge^{71} and Sn^{113}, respectively. The arrangement for the second method (using reflectors) is shown in Fig. 1. The reflector foils were about 0.01 cm thick and their area was about 40 cm^2. Sn^{113} was used as the primary x-ray source for the production of the fluorescence radiation in Zr, Rh, and Ag. Table I gives the energies for the

TABLE I. Energies of the K_α and K_β x-rays in Ga, Zr, Rh, Ag, and In.

Element	Energy in kev K_α	K_β
Ga	9.1	10.2
Zr	15.5	17.6
Rh	19.8	22.6
Ag	21.7	24.8
In	23.7	27.1

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K_α and K_β radiation in these elements. The approximate intensity ratios of K_α/K_β are 5:1. (Since the binding energy of the K shell in Ag is 25.5 kev, only the K_β x-rays of indium are able to produce the fluorescence radiation of Ag.) Conversion electrons from Cs^{137} and Hg^{203} which give linear response were used for calibration purposes.

The pulses from the photomultiplier tube were amplified by a linear, nonoverloading amplifier with a rise-time of 0.25 microseconds and a time constant of 2.5 microseconds. A single-channel pulse-height analyzer was used for the pulse-height selection.

III. RESULTS

Two typical pulse-height distributions are shown in Figs. 2 and 3. The distribution in Fig. 2 was obtained using Ge^{71} and represents the lowest energy measured. Figure 3 is a pulse-height distribution obtained by using fluorescence x-rays from a Zr foil. About 15 percent of the x-ray counts are due to the K_β radiation. Since the K_α and K_β peaks cannot be resolved, a small correction for the evaluation of the true pulse-height maximum which belongs to the K_α x-rays was necessary. This introduces an uncertainty of the fluorescence energy relation of about ± 2 percent.

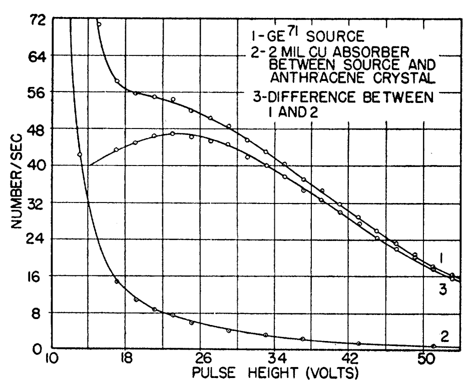

FIG. 2. Pulse-height distribution resulting from the fluorescence radiation of anthracene when excited by x-rays of a Ge^{71} source. The photomultiplier tube noise is responsible for the large number of small pulses. The statistical errors are not indicated since they are smaller than the circles.

Plots of pulse height *vs* energy are shown in Figs. 4 and 5. The arbitrary pulse-height scale is normalized to 624 for the 624-kev Cs^{137} K conversion electrons. The accuracies of the pulse-height determinations are ± 1 percent at 600 kev, ± 2 percent at 200 kev, and ± 5 percent in the region from 10 kev to 30 kev. In the range from 20 kev to 30 kev the Compton effect and the photoelectric effect are of the same order of magnitude, but the Compton events will not be counted unless they are followed by a photoelectric event. The slight broadening of the pulse-height distributions on the low-energy side by Compton events is taken into account in the assignment of errors in this energy range.

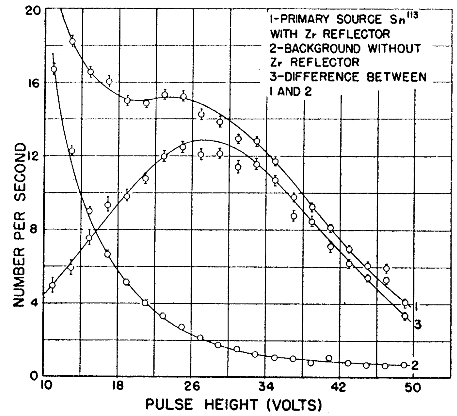

FIG. 3. Pulse-height distribution resulting from the fluorescence radiation of anthracene when excited by x-rays of Zr.

As a check on the calibration of the electronics, the response of sodium iodide to electrons of energies from 20 kev to 660 kev was measured; the response was found to be linear over this region in agreement with previous results.[5,8]

The present experimental response curve (Figs. 4 and 5), is linear above 130 kev with an extrapolation intersecting the abscissa at 23 kev in good agreement with previous experiments.[3,5] It also agrees with the previous curve at lower energies within the accuracy claimed in that experiment, but lies somewhat higher. This agreement suggests that the response to short range electrons incident on the surface of the crystal is not very different from the response to electrons produced within the crystal by x-radiation. The discrepancy between the heavy particle and electron-fluorescence efficiency therefore remains and cannot entirely be attributed to the escape of excitons or photons from the crystal surface, as suggested by Birks.[9]

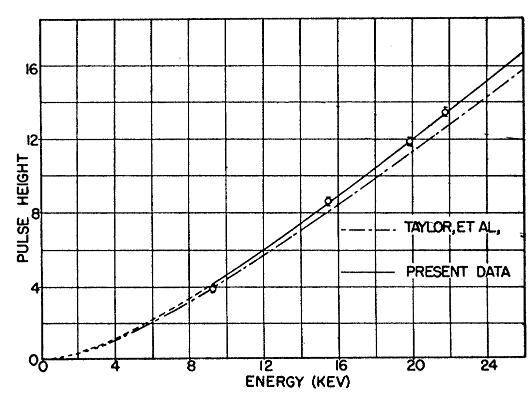

FIG. 4. Pulse heights from the fluorescence radiation of anthracene as a function of electron energy. The arbitrary pulse-height scale is normalized to 624 for 624-kev electrons.

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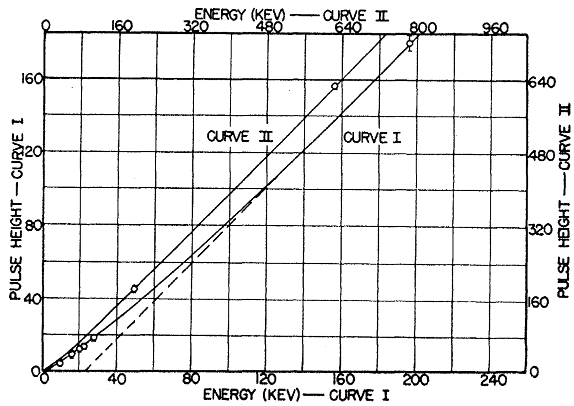

FIG. 5. Pulse heights from the fluorescence radiation of anthracene as a function of electron energy. The arbitrary pulse-height scale is normalized to 624 for 624-kev electrons.

IV. DISCUSSION OF RESULTS

It is known that the fluorescence efficiency of an organic crystal depends on the density of the ionization along the path of the particle in the crystal. Figure 6 is a plot of the specific fluorescence dL/dx as a function of specific energy loss dE/dx for alpha particles, protons, and electrons. The curves for alpha particles and protons were recalculated from the pulse height *vs* energy curves obtained by Taylor *et al.*[5] and Franzen *et al.*,[2] using dE/dx values which were computed from Hirschfelder and Magee's[10] work on the stopping power of protons in hydrogen and carbon. The curve for electrons was calculated from the curve of pulse height *vs* energy obtained in the present experiment. The values of dE/dx for electrons were calculated from Bethe's[11] theoretical formula. These curves show that the specific fluorescence for large dE/dx values depends on the specific energy loss and on the nature of the incident particle.[5]

Theories of the dependence of the specific fluorescence on the specific energy loss have been proposed by different authors.[12] The nonlinear dependence is probably due to quenching of the excitation and ionization in the ionization column. The semiempirical formula of Birks, which gives the connection between dL/dx and dE/dx, reads

$$\frac{dL}{dx}=A\frac{dE}{dx}\bigg/\left(1+B\frac{dE}{dx}\right),$$

where A and B should have the same constant value independent of the nature of the particle. Therefore, particles which have the same specific energy loss should give the same specific fluorescence.

The experimental points for protons and, except for very low energy, for α particles can be accurately fitted by Birks' formula. However, choosing the same value of A for both curves, the B value for protons is slightly larger than that for alpha particles. Recent, very accurate measurements of Cross agree essentially with these results. His data yield for protons a B value of 6.4 and for alpha particles 5.0, if one assumes that $A=1$ in both cases.

In contrast to the proton and alpha curves, Birks' formula does not fit the electron curve. If the constant A is taken the same as for the heavy particles, B can be chosen to fit the response below 150 kev only at the expense of an 8 percent deviation from linearity at 150 kev and a 5 percent deviation at 600 kev. This is outside the experimental error quoted for this region by Hopkins,[3] Taylor *et al.*,[5] and the present authors, all of whom found linearity at least within ± 2 percent above 150 kev.

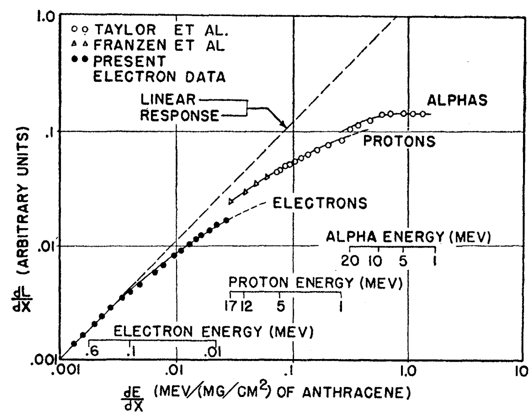

FIG. 6. Variation of the specific fluorescence, dL/dx (expressed in arbitrary units per mg/cm^2), of anthracene with the specific energy loss, dE/dx, of the incident alpha particles, protons, and electrons of different energies. The straight line indicates linear response of the crystal.

The different energy spectra of the secondary electrons from alpha particles, protons, and electrons with the same specific energy loss may provide a possible explanation for their different response.[5]

ACKNOWLEDGMENTS

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