

The Absolute Luminescence Yield for γ -Scintillations in a Naphthalene Crystal with Anthracene

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By means of apparatus calibrated in absolute units, the absolute energy yield of luminescence for γ -scintillations induced in a naphthalene-anthracene crystal by Compton electrons was found to be $0.7 \pm 0.2\%$.

1. INTRODUCTION

THE question of the magnitude of the energy yield of luminescence under excitation by particles has essential theoretical and practical significance. Nevertheless, experimental data on the fraction of the energy of a particle which is transformed into light energy of a scintillation are not yet sufficiently reliable. This question was a topic of discussion even at the time when scintillations under the action of α -particles were observed visually. Ril', in a series of works (see, for example, Reference 1) indicated very high values of energy yield (of the order of 80%) for scintillations in zinc sulphide. Timofeeva, in work carried out under the suggestion of S. I. Vavilov², obtained very much lower values (1-2.5%). In the more recent works of Kallmann and co-workers³, carried out with the use of photo multipliers, a value of 25% was obtained.*

Equally contradictory are the data on the energy yield of luminescence of organic crystals under the action of fast electrons. For anthracene, values of 10%⁴, 3.7%⁵ and 1-2%⁶ are indicated. The first two values refer to integral measurements, i.e., to measurements of the mean intensity under continuous excitation. The last refers to pulse measurements, i.e., of light energy realized in a short scintillation. The reason for the discrepancies between these values, however, apparently can not

be ascribed to the difference in method, since it has been shown⁷ that the afterglow of anthracene for hard excitation is small.

In a majority of the works, data on the energy yield are obtained under various more or less reliable assumptions about the spectral distribution of the luminescence energy and of the sensitivity of the photo multiplier (efficiency of the photocathode) and spectral distribution of sensitivity). In the present work, the task was set insofar as possible to avoid such arbitrary assumptions, and to find all the necessary quantities experimentally.

2. METHODS OF THE MEASUREMENTS

For the determination of the value of the absolute energy yield for scintillations induced by γ -rays, it is necessary to: 1) measure the luminous energy of a scintillation by means of an apparatus which was calibrated in absolute units, 2) compare the measured scintillation with the amount of energy lost in the crystal by the fast electron which resulted upon absorption of the γ -quantum.

The apparatus which served to determine the energy of a scintillation, consisted of 1) a photometric sphere for utilization of all of the light which leaves the crystal, 2) a photomultiplier, 3) a linear amplifier and 4) a discriminator, which analyzes the amplitude of the amplified pulses.

In order that the reading of the discriminator (the amplitude of the output pulse) be proportional to the integral of the input pulse, the time constant of the input circuit of the amplifier was chosen of sufficient length in comparison with the duration of a scintillation. The amplifier was calibrated by means of short light pulses of known energies, expressed in terms of photocurrent of the phototube for steady illumination \times the duration of a pulse.

¹G. I. Born, H. Ril' and K. G. Tsimmer, Dokl. Akad. Nauk SSSR 59, 1269 (1948).

²T. V. Timofeeva, Izv. Akad. Nauk SSSR, Ser. Fiz. 13, 135 (1949).

³I. Broser, H. Kallmann and U. M. Martius, Z. Naturforsch., 4a, 204 (1949).

⁴M. Furst, H. Kallmann and B. Kramer, Phys. Rev. 89, 416 (1953).

⁵J. B. Birks and M. E. Szendrei, Phys. Rev. 91, 197 (1953).

⁶J. I. Hopkins, Rev. Sci. Instr. 22, 29, (1951).

* Note in proof: This question has been treated in an observation by Ril' (N. Ril' and G. Ortman, Zh. Obshch. Khim.) 25, 1697 (1955).

⁷J. A. Jackson, and F. B. Harrison, Phys. Rev. 89, 322, 1953.

The sensitivity of the photomultiplier was determined separately in microamperes per watt of light incident on the photocathode. For this purpose, the photomultiplier was illuminated by a lamp with a known light intensity through a blue filter, selected in order that this source approximately reproduced the energy distribution in the luminescence spectrum. The identical nature of the conditions of light-utilization was assured in that the light from the lamp-standard was passed through an aperture into the photometric sphere and fell on its wall (which was covered with magnesium oxide). Under these very conditions, i.e., with the sphere, the curve of spectral sensitivity of the photomultiplier, needed for the introduction of a correction for the difference in spectra of the crystal radiation and of the standard source, was measured.

The conversion from photo-technological units to energy (units) can be accomplished, if one knows the energy distribution in the spectrum of the lamp, which is specified to sufficient accuracy by its color temperature, and the transmission of the filter.

An exact comparison of the size of a γ -scintillation with the energy lost by an electron presents certain difficulties. On absorption of γ -rays in an organic crystal with relatively small density, the Compton effect plays the basic role. The energy distribution of the Compton electrons, which falls off on the side of large energies, can serve for a crude comparison of the magnitude of a scintillation with the specific energy lost by a particle. For this, one must determine the maximum momentum in the integral distribution curve. However, the measurement of the magnitude of the maximum momentum is connected with some uncertainty, since the limit of the Compton distribution can be washed out by statistical fluctuations in the number of electrons ejected from the photocathode for a single scintillation.

In the present work a coincidence method, borrowed from γ -spectroscopy,⁸ was used. The method consists in the observation of coincidences between pulses originated by Compton electrons and pulses from the scattered γ -quanta. If an electron has energy close to the maximum, its momentum is directed approximately in the direction of the primary quantum, and the scattered quantum flies back at some angle θ with respect to the direction of the primary quantum. For angles θ in the interval $135-180^\circ$, the energy of the scattered quantum is close to $\frac{1}{2}m_0c^2$ and depends weakly on θ . Therefore, if a collimated beam of γ -rays is directed on the investigated crystal *I* (Fig.1) and an auxiliary

crystal *II* with a photomultiplier is set in the path of the quanta scattered through large angles, and only those scintillations are recorded in the measured crystal which coincide with scintillations in the auxiliary crystal, then the differential distribution of pulse sizes must give a narrow maximum (in the case of monochromatic rays), which corresponds to the distinct energy of the electrons.

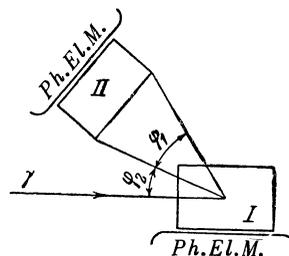


FIG. 1. Scheme of observation of the scattered γ -quanta.

Even for angles $\phi_1 = \pi - \theta$ of the order of $60-80^\circ$, the width of the maximum, which is dependent upon the finite dimensions of the second crystal (for example, for $\phi_1 - \phi_2 = 40-50^\circ$) does not exceed 8-10%, i.e., is of the same order as the width due to fluctuations. The determination of the position of the maximum can thus be made to an accuracy fully sufficient for our purposes.

The integral curve of the distribution obtained by the method described, with excitation by γ -rays from Co^{60} (1.17 and 1.33 mev), (and the differential curve calculated from it) is shown in Fig.2.

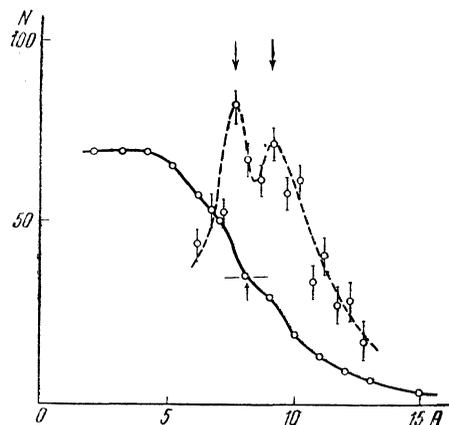


FIG. 2. Integral curve (solid) and differential curve (dashed) obtained by the method of coincidences. (Co^{60} radiation)

3. MEASURING APPARATUS

The crystal for the measurements was placed in

⁸R. Hofstadter and J. A. McIntyre, Phys. Rev. 78, 619(1950).

a photometric sphere (Fig. 3), covered from within

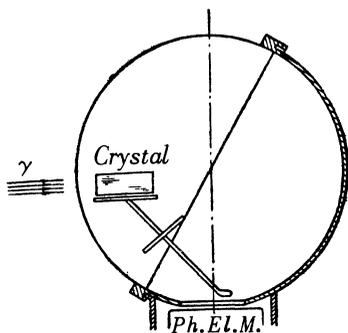


FIG. 3. Diagram of the photometric sphere .

with powdered magnesium oxide. The half of the

sphere exposed to the source of γ -rays was spun from aluminum and had a wall thickness of 0.2 mm in order to minimize the scattering of γ -rays in the wall of the sphere. The sphere had an opening (2 cm diameter) against the window of the photomultiplier, and a small aperture for admission of the light from the standard lamp. A small internal shield screened the photocathode from direct incidence of light from the crystal.

The electronic part of the apparatus is schematically shown in Fig. 4. A cathode follower was built within the housing of the photomultiplier. The parameters of the amplifier are: amplification factor-from 3 to 200 (for most measurements ~ 30), pulse rise time (time constant of the input circuit)-of the order of a few microseconds.

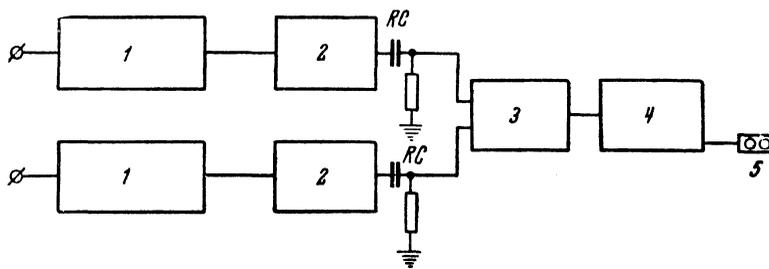


FIG. 4. Block diagram of the electronic apparatus.
1-Amplifier; 2-Discriminator; 3-Coincidence circuit;
4-PS-64; 5-Mechanical counter; RC=0.5 μ -sec.

The amplitude of the pulses was measured with a simple integral discriminator. The pulses given by the discriminator (rectangular), were further differentiated and, together with the primary pulses formed in the second channel, were fed to the circuit which selects the coincidences.

A drawback to the system is the large number of accidental coincidences due to the dark noises of the second multiplier, which must register relatively small impulses from γ -quanta with energy ~ 0.25 mev. At the same time, it is not possible to reduce the duration of the pulses, since the rise time of the amplifier must be sufficiently great for the integration of all of the studied pulses. A more ideal system would be to have a coincidence circuit before the amplifier which would operate with the passing through to the amplifier of previously delayed pulses.

The Co^{60} compound ($\sim 150\text{mC}$) was placed in a lead shield with a 4 mm bore collimator in a lead block 20 cm long. The detector of the scattered γ -quanta was a crystal of NaI-Tl mounted near the

photocathode of the photomultiplier.

4. CALIBRATION OF THE AMPLIFIER AND OF THE PHOTOMULTIPLIER

The calibration of the amplifier was accomplished by means of a mechanical generator of short light pulses.⁹ The entrance slit S_1 (Fig.5), illuminated by a projection lamp fed through a stabilizer, is imaged on the plane of the exit slit S_2 by a long focal-length objective ($f=50\text{cm.}$). The slits were arranged parallel to one another. A rotating plane mirror was set in the path of the beam so that the photomultiplier, located behind S_2 , registers the light pulse. The time of passage of each point of the image past the exit slit equals

$$\tau = S_2/4\pi vL, \quad (1)$$

where S_2 is the breadth of the exit slit, L -the length

⁹S. M. Raikii, J. Exper. Theoret. Phys. USSR 22. 780 (1952)

of the rotating arm ($L=746\text{mm}$) and ν the number of revolutions per second of the motor, which could reach 120. The energy contained in each impulse is

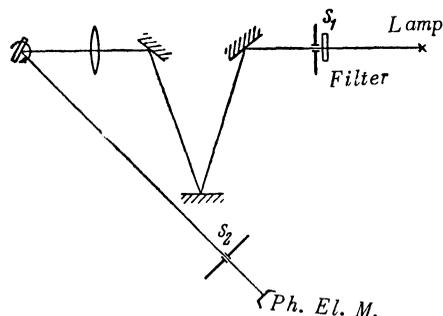


FIG. 5. Plan of the mechanical generator of light pulses.

determined by the product of τ and the magnitude of the total light flux in the image. This light flux is proportional to the strength of the current from the anode of the photomultiplier and can be measured when the entire flux is steadily incident on the cathode (with the mirror still).

It should be noted that, owing to statistical fluctuations in the photocurrent of the photomultiplier (on account of the small number of electrons from the photocathode for a single impulse) the pulses in the output of the photomultiplier have some scatter in amplitude. For calibration, a reading of the discriminator was taken which corresponds to the mean of this dispersion, i.e., to the point where the integral curve of displacements has the largest slope.

In order to allow for the effect of the duration of the pulses, the dependence of A/τ (A is the reading of the discriminator) on τ was measured. The result is described in Fig. 6. Had the pulses been

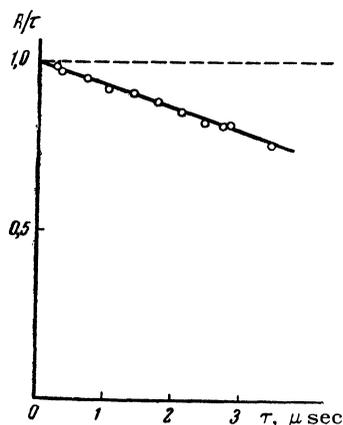


FIG. 6. Dependence of A/τ on the duration of the pulse τ . fully "integrated," then A/τ would have to be constant.

The calibrating pulses had a duration of $2.80 \mu\text{sec}$. For them, A/τ amounts to 0.82 of the value of this ratio for infinitesimal τ . This was accounted for in the calibration. As a result of the measurements it was found that for very short pulses a pulse size of $0.33 \times 10^{-6} \mu\text{A sec}$ corresponds to one scale division.

For the determination of the energy sensitivity of the photomultiplier, it was illuminated through the 1.68 mm diameter aperture in the photometric sphere by a standard light source—an incandescent lamp with a BG-12 filter. The light intensity of the lamp was determined by an AEI (All-Union Electrical Engineering Institute) colorimeter and was found equal to 13.2 candles. The color temperature of the lamp (2600°K) was measured on the same colorimeter by the method of the red-blue ratio. The tungsten filament in the lamp can be considered a gray body to an accuracy of 1%. The curve given in Fig. 7 represents the product of the energy distribution in the radiation of the lamp and the transmission of the filter, i.e., the spectrum of the radiation of the standard source.

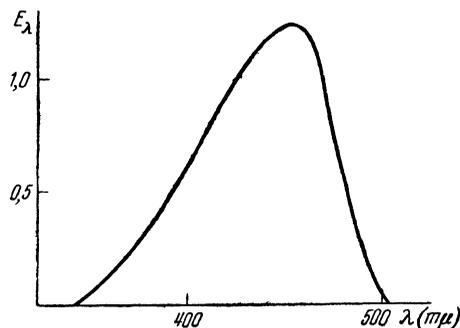


FIG. 7. Energy distribution in the spectrum of the standard source.

The conversion from light units to those of energy can be carried out in the following manner. The lamp (without filter) sends out into unit solid angle the flux

$$F(\text{lumen}) = k_0 \int V_\lambda \Phi_\lambda(\text{watt}) d\lambda; \quad (2)$$

here V_λ is the factor of relative visibility for the average eye, k_0 is the reciprocal of the mechanical equivalent of light, $k_0=683 \text{ lum/W}$. Considering (2), we obtain that the flux in watts, emitted in unit solid angle by the standard source, is equal to $2.05 \times 10^{-3} \text{ W/sterad}$.

The light from the standard source, set at 5.605 m from the hole in the photometric sphere, excited a current of $0.48 \mu\text{A}$ in the photomultiplier. Under these conditions the flux into the aperture amounted to $1.44 \times 10^{-10} \text{ W}$, so that a current of $1 \mu\text{A}$ is ex-

cited by a flux of $3.00 \times 10^{-10} \text{ W}$, distributed in the spectrum of the source.

The curve of the relative spectral sensitivity of the photomultiplier (with the photometric sphere) f_λ , necessary for the calculation of the difference in the spectra of the standard and of the crystal, was measured on a Hilger double monochromator by means of comparison with a thermal column. A PRK-4 lamp and an incandescent lamp were used as the source. The curve f_λ of the photomultiplier with the sphere (Fig. 8, solid line) differs from the sensitivity of the photomultiplier under direct incidence of light on the photocathode in the region

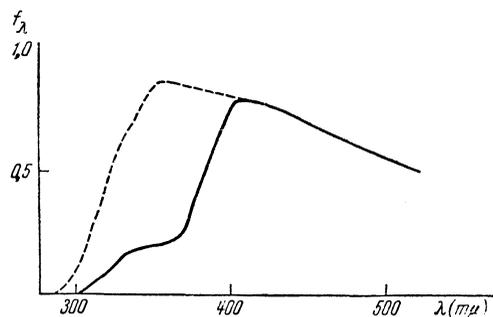


FIG. 8. Spectral sensitivity of the photomultiplier (solid curve-with the photometric sphere, dashed-without the sphere).

300-400 μm (dashed curve), because of some rise in the absorption of MgO in this range of the spectrum.

Proceeding on the assumption, corroborated by measurements published in the literature¹⁰, that the luminescence spectrum of the crystal for γ -excitation is identical to the photoluminescence spectrum, the luminescence spectrum of the crystal was measured with excitation by the 365 μm line of a mercury lamp (Fig. 9), to get the correction for the difference in spectra of the crystal and of the standard source. Multiplying the distribution of energy in the spectra of the crystal and of the standard by f_λ , and comparing the areas under the curves obtained, one can find the difference in utilization of energy by the photomultiplier. It was found that light of luminescence with the same energy as the standard must give a 9% larger photocurrent. Introducing the appropriate correction, we find that $1 \mu\text{A}$ of photomultiplier current corresponds to a luminescence output of the crystal in the sphere equal to $2.76 \times 10^{-10} \text{ W}$.

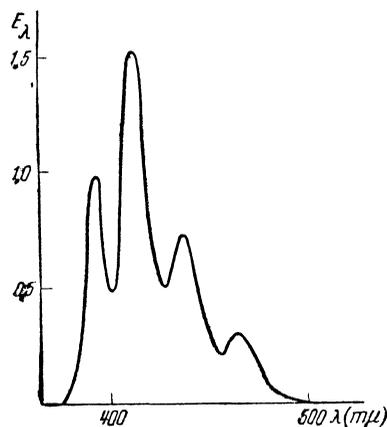


FIG. 9. Energy distribution in the photoluminescence spectrum of a naphthalene-anthracene crystal.

5. RESULTS OF THE MEASUREMENTS

During the measurements of the energy of scintillation according to the method described in section 2, the angle $\phi = \pi - \theta$, corresponding to the direction through the middle of the auxiliary crystal, was approximately equal to 70° . With this, the mean energy of the Compton electrons, corresponding to γ -rays from Co^{60} (1.17 and 1.33 mev), came to approximately 0.95 mev.

The crystal of naphthalene +1% anthracene was placed inside the sphere with the long side along the beam of γ -rays. The range of electrons with 0.95 mev energy in the crystal, which has near unit density, amounts to about 2.5 mm. which is substantially less than the dimension of the crystal in the direction of the trajectories of the electrons.

The measured pulse height which was determined by the method described in section 2, was found equal to $A=11.7$ divisions on the discriminator*, for the same voltage on the photomultiplier as used during the calibration. Converting the value of a division into energy gives: 1 division = $2.76 \times 10^{-10} \times 0.33 \times 10^{-6} \text{ Wsec.} = 0.57 \times 10^{-3} \text{ mev}$. The energy of the scintillation is hence equal to $11.7 \times 0.57 \times 10^{-3} = 0.67 \times 10^{-2} \text{ mev}$ and the value of the absolute energy yield is 0.70%.

The mean square error of this result, due to the accidental errors in all phases of the measurement, does not exceed 10%. But systematic errors are possible on account of insufficiently close maintenance of the conditions identical to those during calibration: a certain difference is probable, for

¹⁰J. C. D. Milton and R. Hofstadter, Phys. Rev. 75, 1289 (1949); F. B. Harrison and G. T. Reynolds, Phys. Rev. 79, 732 (1950).

*This value pertains to the final series of tests, for which the entire distribution curve was not taken down, but only the inflexion point, and therefore does not correspond to the curve in Fig. 2.

example, in the utilization of the light from the crystal and from the external source. To all appearances, owing to the precautions taken, the systematic error should not exceed 20-30%. Such accuracy must also be ascribed to the result derived above. It is necessary to stress likewise, that the measured value pertains to the energy which escapes from the crystal. Here there are not taken into account losses on reabsorption and on "capture" of luminescence due to total internal reflection. The latter, however, could hardly be effective, since the crystal had a rough surface.

If we use the measured ratio of the scintillation intensities in anthracene, and in naphthalene with anthracene* (1:0.41), and disregard the small shift of the luminescence spectrum of the anthracene crystal in comparison with the spectrum of anthracene and naphthalene, then for the absolute energy yield of the anthracene crystal under excitation by electrons with energy ~ 1 mev, we obtain 1.7%. This value fits in with the results of the work of Reference 6, and is lower than the other values quoted in the literature.

6. DISCUSSION OF THE RESULTS

The theoretical interpretation of the size of the energy yield of luminescence on excitation by charged particles must be based on the theory of ionization losses. The problem of excitation of luminescence by charged particles reduces to the question of the division of ionization losses over losses strictly for ionization and losses for excitation. The next stage must end in a clarification of the efficiency of excitation of luminescence by ionization and by excitation of atoms and molecules.

This problem is very complex, on account of the necessity of taking into account secondary particles of low energy, and is not completely solved even as concerns the older question of the number of ions formed by a moving charged particle (see, for example, Reference 12). The empirical result consists in a proportionality between the number of ions formed and the particle energy loss. It is natural to assume that a similar proportionality likewise exists for the number of effectively excited molecules. Birks¹³ makes such an assumption in his

works, in which, for explanation of the experimentally observed dependence of the intensity of scintillations on the energy and type of particle, an additional assumption on quenching has to be introduced. Birks assumes that, together with the transition of molecules into excited states ("exciton" formation), a charged particle gives rise to the formation of "damaged" molecules, the number of which is likewise proportional to the specific energy loss. These "damaged" molecules are able to trap excitons, which thus leads to quenching. Birks' theory is in good agreement with the experimental data on the dependence of the intensity of scintillations on the energy of the different particles, which justifies its initial assumptions. Thus it is possible to regard the energy given up to excitation of luminescence as amounting to a definite portion of the general loss of energy per given element of path of the particle, independent of its energy.

The other side of the question concerning the theoretical computation of the ratio of losses for excitation of luminescence to the overall energy losses of a particle, i.e., the question of the size of the energy output of luminescence, presents no less interest. There is not yet sufficient data, apparently, for an exhaustive answer to this question. An analysis of the possible contribution of the various processes in excitation of luminescence, however, seems desirable.

For organic crystals it is natural to make the assumption that the ionization and subsequent recombination of molecules is not very effective with regard to the excitation of luminescence. Recombination processes, if also able to give light in organic materials (experimental data on such luminescence seems to be lacking), then must have a duration considerably in excess of the lifetime of an excited state. Consequently, the contribution of these processes to the intensity of scintillation is slight. Ionization processes are essential in this case insofar as they provide secondary particles which are able to excite luminescence.

Excitation processes can be more or less definitely separated into two types: "long range" excitation, when a molecule is excited as a whole (in the case of most organic molecules, excitation of the system of π -electrons occurs), and excitation with "local" emphasis, when to a first approximation one can concentrate on a single atom of the molecule, disregarding its bonds with the other atoms. The question, with what probability does the excitation energy of atoms go over into excitation of a molecule, is not clear at the present time and requires further investigation.

It is essential to note that the energy lost by a

*Note that our comparative measurements for anthracene, stilbene and phenanthrene (100:45:25) conform nicely with the data of Ref. 11, (100:45:30).

¹¹ H. Kallmann, M. Furst and M. Sidran, *Nucleonics* 10, No. 9, 15, (1952).

¹² E. Fermi, *Nuclear Physics*, (Univ. of Chicago notes, 1952).

¹³ J. B. Birks, *Proc. Phys. Soc. (London)*, A64, 874(1951); *Phys. Rev.* 86, 569(1952).

particle for excitation with long range effect can be comparatively large in some cases. For the estimation of these losses, one can use Fermi's theory¹⁴ of ionization losses, where the medium is considered continuous and is characterized by macroscopic parameters.

Let a particle (for example, an electron) be moving with velocity v in the direction of the x axis. The energy flux per unit length through the surface of a cylinder of radius ρ , the axis of which is the trajectory of the electron, is given by the expression^{15,16} (for the condition $s\rho \ll 1$)

$$-\frac{dE}{dx} = \frac{ie^2}{2v^2} \times \int_{-\infty}^{\infty} \left(\frac{1}{\epsilon(\omega)} - \beta^2 \right) \left(-i + \frac{2}{\pi} \ln \frac{2}{\gamma s \rho} \right) \omega d\omega, \quad (3)$$

where $\epsilon(\omega)$ is the dielectric permeability of the medium (generally speaking, complex), $\beta=v/c$, $\gamma=1.78$ and $s=(|\omega|/v) (\beta^2 \epsilon - 1)^{1/2}$. If $\beta^2 \epsilon < 1$, then a factor $-i$ comes out of the parentheses and $s=(|\omega|/v) (1-\beta^2 \epsilon)^{1/2}$

In order to be able to make a simple estimate, we consider that case (which is found, really, in the limit of the experimental conditions) where the absorption over a wavelength in the frequency range considered is small. Then the dielectric permeability can be approximately expressed through the index of refraction n and the coefficient of absorption α in the following way:

$$\epsilon(\pm\omega) \approx n^2 (1 \pm i\alpha\lambda), \quad (4)$$

where λ is the wavelength in the medium, divided by 2π . For the condition

$$|\alpha\lambda (\beta^2 n^2) / (\beta^2 n^2 - 1)| \ll 1$$

the expression (3) gives (see, for example, reference 17)

$$-\frac{dE}{dx} = \frac{e^2}{v^2} \int_0^{\infty} \left[\frac{\beta^2 n^2 - 1}{n^2} + \frac{\alpha\lambda}{\pi n^2} \left(\ln \frac{4\beta^2}{3.17 (\rho/\lambda_0)^2 (\beta^2 n^2 - 1)} - \beta^2 n^2 \right) \right] \omega d\omega \quad (5)$$

($\lambda_0 = \lambda_0/2\pi$, λ_0 is the wavelength in vacuum). For particles of low energy, when $\beta^2 \epsilon < 1$, the first term

in (5) (losses on absorption of Cherenkov radiation) is absent.

In order to obtain the energy converted into luminescence, it is necessary to take into account the dependence of the luminescence yield on the exciting frequency. According to Vavilov's principle¹⁸, this dependence can be expressed in the following manner: $\eta = \eta_0 \omega_1/\omega$ for $\omega > \omega_1$, $\eta=0$ for $\omega < \omega_1$. Having substituted these values in (5), we get for the energy of luminescence per unit length (for $\beta^2 \epsilon < 1$)

$$\frac{dF}{dx} = \frac{e^2}{v^2} \eta_0 \omega_1 \times \int_{\omega_1}^{\omega_2} \frac{\alpha\lambda}{\pi n^2} \left(\ln \frac{4\beta^2}{3.17 (\rho/\lambda_0)^2 (\beta^2 n^2 - 1)} - \beta^2 n^2 \right) d\omega \quad (6)$$

Here ω_1 is the frequency which approximately corresponds to the maximum of the fluorescence, ω_2

is the frequency of ionization of a molecule (assuming that $\eta(\omega)=0$ for $\omega > \omega_2$).

For computation of the value of dF/dx we do not have sufficiently complete data on the value of the coefficient of absorption and its dependence on frequency, and likewise on the quantity ω_2 and on the output $\eta(\omega)$ for $\omega > \omega_2$. The following data can be used for a rough estimate. Let the electron have an energy of ~ 0.01 mev ($\beta^2 = 0.04$). The coefficient of absorption for organic crystals (for instance, anthracene) has the order of 10^5 cm^{-1} , i.e., $\alpha\lambda \approx 1$. For the index of refraction we assume $n^2 \approx 3$. The frequencies are $\omega_1 \approx 5 \times 10^{15} \text{ sec}^{-1}$ ($\sim 4000 \text{ \AA}$) and $\omega_2 \approx 20 \times 10^{15} \text{ sec}^{-1}$ ($\sim 1000 \text{ \AA}$). The quantum yield $\eta_0 \approx 1$, $\rho \approx 10^{-7} \text{ cm}$. Then $dF/dx \approx 0.2$ mev/cm. The general ionization losses for an electron of such energy in a substance the type of anthracene amount to $(dE/dx)_{\text{ion}} \approx 25$ mev/cm. Thus the ratio

$$a = (dF/dx) / (dE/dx)_{\text{ion}} \approx 1\%.$$

In order to compare this estimate with the value of the yield, one must take into account the corresponding losses of the secondary particles. Here one can be guided by that fact, known from experiments on gases, that only about half of the energy of a particle is expended in ionization. If one assumes that the same sort of relation is maintained for crystals, then the total energy of the secondary

¹⁴ E. Fermi, Phys. Rev. 57, 485(1940); see also the reference collection (Problems in Modern Physics)(USSR) 7, (1935).

¹⁵I. E. Tamm, Phys. USSR 1, 439(1939).

¹⁶P. E. Kunin, Collected Work *Meson* (1947) (in Russian).

¹⁷P. Budini, Nuovo Cim., 10, 236 (1953).

¹⁸S. I. Vavilov, Z. Physik 42, 311 (1927).

particles, which originate per element of path Δx , is equal approximately to $\frac{1}{2}(dE/dx)\Delta x$. If for all of the secondary particles, the quantity a is the same, then the portion of the losses to long range excitation can amount to $\sim 3a/2$.

This estimate gives only the lower limit of the losses to excitation. Actually, for secondary particles of low energy in the neighborhood of the binding energy of the electrons in the molecule, the portion a of the losses for excitation of luminescence must increase. This can be concluded by analogy from the form of the functions of excitation and ionization of atoms by electrons. The estimate made here, however, shows that possibly a significant part of the excitation of luminescence is explained by the mechanism indicated. The question as to how, along with this, a linear depend-

ence between the number of excited molecules and the energy of a particle comes about, requires a special analysis. Together with that, the occurrence of the above-mentioned processes of intramolecular conversion of excitation energy is not excluded*.

From these deliberations it is clear that a comparison of the optical properties of luminescent materials (coefficient of absorption and luminescence output for various frequencies of excitation) with their ability to luminesce under the influence of charged particles has essential value for the further clarification of the question.

*We note that we have neglected here processes of extinction, which must be taken into account especially for a high density of ionization.

Translated by R. L. Eisner