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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

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ЕФИ-65(74)

M.P. LORIKIAN

RELATIVISTIC ELECTRONS TRANSIT
TROUGH INHOMOGENEOUS MEDIA



YEREVAN PHYSICS INSTITUTE

Scientific Report EM-65(74)

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Yerevan 1974

М.П. ЛОРИКЯН

ПРОХОЖДЕНИЕ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ
ЧЕРЕЗ НЕОДНОРОДНЫЕ СРЕДЫ

В работе обсуждаются экспериментальные результаты некоторых вопросов прохождения релятивистских электронов как через слоистые, так и пористые среды. Приводится анализ образования при этом переходного излучения и интерференционных явлений, обнаруженных в стопках из алюминиевых пластин, а также обсуждается влияние многократного рассеяния на переходное излучение.

Ереванский физический институт
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Scientific Report ЕФИ-65(74)

M.P. LORIKIAN

RELATIVISTIC ELECTRONS TRANSIT THROUGH
INHOMOGENEOUS MEDIA

In this work the results of the investigation of X-ray transition Radiation both in laminar and porous media are presented. The experimental data are shown to agree with theoretical predictions.

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The discussion of experimental data on the transit of relativistic electrons through both the laminar and the porous media is given. The generated transition radiation and interference phenomena in stacks of aluminium foils are analysed. The effects of multiple scattering on the transition radiation are discussed as well.

1. The physics of electromagnetic processes attending the transit of charged particles through the matter is of interest not only from the purely cognitive point of view, but also because of the applications the effects of this branch find in different fields of science and engineering. On the other hand, the theoretical foundations of these processes are well developed and it is always possible to make a quantitative comparison between experimental data and theoretical predictions.

The transition radiation is one of the most interesting phenomena in this field. The generation of such a radiation in optical band was first considered by Ginzburg and Frank^[1] in 1947. Some time later G.Garibian^[2] and K.A.Barsukov^[3] theoretically showed, that the intense radiation is also generated in X-ray frequency range when relativistic particles traverse the interface between two media.

2. The formula for the intensity of X-ray transition radiation produced in a stack of N a -thick plates with the spacing b between them could be written in its most general form [4,5,6] as

$$\frac{dS}{d\Omega} = N \frac{4e^2(\omega_p'')^2}{\pi c \omega^3} \sum_{k=0}^{\infty} \frac{(k+d) \sin^2 \left[\left(k+d + \frac{\omega''}{\omega} + \frac{\omega}{\omega_p'} \right) \pi \alpha / p \right]}{\left[k+d + \frac{\omega_p''}{\omega} + \frac{\omega}{\omega_p'} \right] \left(k+d + \omega/\omega_p' \right)^2} \quad (1)$$

where $d = \left\{ \frac{\omega a}{\omega} + \frac{\omega}{\omega_p'} \right\} - \left(\frac{\omega a''}{\omega} + \frac{\omega}{\omega_p'} \right)$,

$$\omega_p'' = \frac{p \omega_0^2}{4\pi v} \quad \cdot \quad \omega_0'' = \frac{a \omega_0}{4\pi v} \quad \cdot \quad \omega_p' = \frac{4\pi v}{p(1-\beta^2)} \quad \cdot \quad p = a + b$$

$\omega_0 = \frac{4\pi N e^2}{m}$ is the plasma frequency of a medium, e - the charge of electron, N is the number of electrons per 1 cm^3 and ω is the frequency of quanta emitted.

The curly brackets in the expression for d give the biggest integer for the number in brackets. The region of the applicability of this formula is specified by following conditions:

$$n \gg \frac{\omega_p'}{\omega}, \quad \left(\frac{a}{p} \right)^{3/2} \frac{\omega_0}{2} \ll \omega_p' \ll \frac{4\omega^2}{\omega_0^2} \quad (2)$$

The angular distribution of this radiation has a sharp maximum at an angle $\Theta \sim \sqrt{1-\beta^2}$ with reference to the direction of particle motion.

Important in the physics of transition radiation are characteristic lengths called the radiation formation zones in vacuum and in a medium.

$$Z_{med} = \frac{c}{\omega(1-\beta^2 + \frac{\omega_0^2}{\omega^2} + \theta^2)}, \quad Z_{vac} = \frac{c}{\omega(1-\beta^2 + \theta^2)}$$

These expressions have a simple physical meaning. The particle traversing the interface between two media emits transition radiation quanta not instantaneously on the interface, but on the definite lengths of its path on either side of the interface. These sections of particle path constitute the formation zones in these media.

3. Not to go into details of experimental arrangement we shall but note, that the measurements in (5 ÷ 20) KeV range were made with the help of multicell proportional chamber and in (20 ÷ 120) KeV range by $\text{NaI}(\text{Tl})$ scintillation spectrometer. The arrangement was repeatedly calibrated by means of standard γ -sources. FWHM for proportional chamber made 16% at the γ -energy of 13.8 KeV and $\approx 30\%$ for scintillation counter at the γ -energy of 60 KeV. Prior to the discussion of measurement data we give in Fig. I as an illustration some typical transition photon events in streamer chamber with Xe admixture. To separate transition photons, the electrons were deflected upward by a small bending magnet placed after the radiator.

a) Lamellar radiators [7,8,10]

To take into account the contribution of background, each run included measurements of radiation spectrum from a solid radiator of equivalent thickness which was then subtracted from the lamellar radiator data. The spectra given are plotted with due regard for the efficiency of the detection of multiple photons as one photon and for a finite resolution of spectrometer.

In Fig. 2. (a,b,c,d,e) the spectra of transition radiation

of 3 GeV electrons in (5 ÷ 20) KeV frequency range are given for a stack of 230 Al foils each 8μ thick with following spacings between adjacent foils: 1mm; 0.5mm; 0.5mm; 0.1mm; 0.05mm.

At least two maxima are seen in the figure that grow less distinct with the decrease in foil spacing. The positions of maxima remain the same in all cases, the foil spacing varying noticeably. Since the thickness of foils was unchanged during the measurements and the spacing varied on a large scale, these maxima are, presumably, due to the interference of the radiation from two boundaries of each foil.

It follows from the figure that the total intensity of transition radiation decreases as the spacing decreases. This phenomenon could be explained by the interference of radiation from different foils.

In the same figure we plotted by dark circles the scintillation spectrometer data. The agreement between the data obtained by different techniques is highly remarkable, as we have not made their artificial lacing.

In the same figure the full-drawn lines represent theoretical curves calculated by transition radiation formula taking into account the absorption^[9]. The theoretical spectra are seen to have also the interference maxima positioned just as in experimental spectra. A slight divergence for large values of β in (15 ÷ 25) KeV range is apparently due to the errors in the estimation of multiple photon effect and should be taken into account especially for larger values of the mean photon number.

It follows likewise from theoretical spectra, that the total intensity of transition radiation falls with the decrease of β , and the positions of maxima also remain unchanged. For

$\beta = 0.1\text{mm}$ and 0.05mm the experimental errors are too great the interference to be observed. It should be noted that for these spacings the accuracy of foil interposition is low and the smearing of interference pattern may take place due to the sticking of foils. Thus, the irregularities of foil spacings as well as the experimental errors render the observation of interference phenomena impossible for small β .

In Fig.3 (a,b,c,d,e) marked by dark circles, transition radiation data as taken by scintillation counter are shown in the frequency range $\hbar\omega \geq 25$ KeV and spacings $\beta = 1\text{mm}; 0.5\text{mm}; 0.25\text{mm}; 0.1\text{mm}$ and 0.05 mm respectively. In the same figure several points from Fig.2. are plotted for comparison. ($\hbar\omega < 25$ KeV) (blank circles). The radiation spectra in frequency range $\hbar\omega > 25$ KeV show smooth decrease, i.e. in this frequency range the interference phenomena are not observed in transition radiation spectra. In the same figure we give theoretical spectra of transition radiation (full-drawn lines) allowing for the radiation absorption in the lamination.

Theoretical and experimental data are in good agreement for large β ; for $\beta = 0.05$ mm and $\beta = 0.1$ mm the experimental points are somewhat higher than the corresponding theoretical ones owing to the irregularities of spacings between foils.

In Fig.4 the β - dependences of the total number of transition photons are given in different frequency ranges of photons. We see, that with the increase of β the intensity of transition radiation shows a steep rise with the subsequent development of a plateau. The total intensity of transition radiation in (5-20) KeV frequency range grows slower than that in the (20-100)KeV range i.e. the plateau is reached appropriately in the latter case sooner

than in the former. Such a behaviour of the total intensity with the increase of β follows from the fact, that the radiation formation zone in the air for lower energy photons exceeds that for higher energy photons. The calculations show that the β values at which the photon number curve reaches the plateau coincide with radiation formation zones in these frequency intervals.

Thus, we can conclude that experimental data are in good agreement with transition radiation theory.

Recurring again to the interpretation of interference peaks we note that the interference from different foils does not lead to new maxima in the spectrum or to any changes in the form of maxima, but only suppresses all the radiation spectrum, the soft part of spectrum being suppressed stronger than the hard one. This phenomenon admits the following interpretation: to form a transition photon of frequency ω_0 , the particle path in air equal to $\sum_{aiz}(\omega)$ is necessary. When the spacing between foils is much lesser than $\sum_{aiz}(\omega)$, then the photons will take two foils as one and the intensity of radiation at this frequency will reduce. If $\beta \ll \sum_{aiz}(\omega)$ for all the stack, then the intensity of transition will not be high on this frequency.

It should be noted then, that in this case the interference of radiation from both boundaries of each plate will not increase essentially the intensity of transition radiation.

Let us now discuss the measured dependencies of transition radiation spectra on the number of foils n as given in Fig.5. The radiator used consisted of $\rho = 1,28/\text{cm}^3$ dense organic foils of following composition: Cl-44%, S-6,5%, C-42%, H-7%.

The thickness of foils was $a=20\mu$ and the spacing between them made 500μ . The data for $n=32$ were taken in $\hbar\omega > 5\text{KeV}$ range and for other values of n in $\hbar\omega > 20$ range.

No noticeable interference is observed in this case in transition radiation spectra. The single maximum in the spectrum for $n=32$ is due to the absorption of soft photons in the radiator and in the material of helium sack windows and of counter aperture.

In the same figure the full-drawn lines represent the theoretical spectral distributions with absorption^[9] for $n=32$ and $n=125$. Good agreement is again observed between theory and experiment. The discrepancy for higher frequency values is connected with the multiple photon effect and the finite resolution of spectrometer. The hardening of spectra with the increase of n is due to the absorption of soft photons in the radiator. As an illustration we give in Fig.5 the calculated spectra (dashed lines) for $n=63, 125$, and 595 using the spectrum for $n=32$ with due regard for photoabsorption and Compton scattering in the radiator itself. Again good agreement between calculated and measured spectra are noticed.

In Fig.6 the radiation spectra as measured with the scintillation spectrometer are given for $n=64$ radiator at different energies of electrons: $E=1.0$ GeV (blank circles); $E=2.0$ GeV (dark circles); $E=3.0$ GeV (blank squares) and $E=4.0$ GeV (dark squares). The radiation spectra are seen here to slightly differ one from the other for $E \geq 2,0$ GeV. This decrease in the radiation intensity growth with the increase of particle energy is better seen in Fig.7, where the E -dependence of total photon number is given. This phenomenon is explained by the radia-

tion interference in the stack.

Let us now consider the effect of multiple scattering on the transition radiation^[10]. The multiple scattering of 600 MeV electrons in the radiator consisting of 240 μ m paper sheets was reported^[11, 12] to greatly increase the intensity of transition radiation.

This radiator is by far not an optimal one, as the zone of radiation formation in paper makes about 1μ m for 670 MeV electrons in (20 \div 50) KeV photon frequency range, i.e. (1 \div 5) μ m paper sheets are necessary for the effective generation of transition radiation. The rest of the sheet thickness only increases the bremsstrahlung background and the probability of secondary radiative processes. The radiator used in our experiment with 680 MeV electrons consisted of 50 paper sheets with $b=2$ mm spacing. As an equivalent radiator we used the compressed stack of the same paper or the wooden bar of equivalent thickness.

In Fig.8 we give radiation spectra recalculated for one sheet. The measurements were made with laminar radiator (blank circles) and with equivalent radiator (crosses). Full-drawn line represents calculated transition radiation spectrum and dashed line represents the spectrum of resonance radiation taking into account the multiple scattering^[12]. The experimental data taken from Ref. [12] are denoted by squares. The theoretical spectra are also taken from Ref. [12].

It appears from the figure, that the predicted transition radiation was not observed in this experiment owing to the smallness of its contribution in comparison with experimental errors. Meanwhile, if the enhancement of radiation intensity on account of multiple scattering took place, i.e. the dashed line spectrum were the case, we should have observed it. as the expected

number of photons was seen to exceed the experimental errors.

It should be noted once again, that owing to the smallness of experimental errors this exceeding in the (20 \div 50) KeV frequency range would have been observed irrespective of the nature of background.

In the same figure we show bremsstrahlung spectra calculated by Bethe-Heitler formula (dot-dashed line) and by Ter-Mikaelian formula^[17] (two dot-dashed line).

In the same figure we plotted by oblique crosses the measurements of bremsstrahlung in an equivalent radiator, i.e. the data corresponding to crosses with subtracted hall background. So, our results are seen to be in good agreement with the theory of bremsstrahlung in $\hbar\omega < 30$ KeV frequency range in absolute value too. In $\hbar\omega < 30$ KeV frequency range the experimental points lie slightly higher, but we can assume this agreement to be satisfactory for all frequencies as the theory predicts strong suppression of bremsstrahlung in the soft photon region.

Thus, our experimental data testify against the influence of multiple scattering on the transition radiation for electron energies up to 3 GeV.

To end the discussion of transition radiation data in regular and plane-parallel spaced foil media we conclude, that all the effects connected with this radiation are well described by transition radiation theory in wide energy range of electrons and performance of radiators^[5,9]. 18,19.

b) Porous radiators (styrofoam)

The transition radiation in porous materials was experimentally discovered^[15,16] by our group in 1969. The importance of the investigation of transition radiation in these radiators is

connected not only with the fact, that they help to understand the physics of phenomenon, but also because of the opportunity to utilize them as radiators in particle detectors.

We have shown in first experiments already that in styrofoam radiator of density $\rho = 0.04 \text{ g/cm}^3$ the number of generated transition photons is, at least, no less than that for laminar radiator with almost optimal performances.

In Fig.9 the transition radiation spectra for 2cm thick styrofoam of density $\rho = 0.04 \text{ g/cm}^3$ are shown for 1GeV, 2GeV and 3 GeV electrons in the photon energy interval (5 ÷ 125)KeV. The blank figures represent data taken by proportional counter, the dark ones—by NaJ(Tl) crystal. (Circles correspond to $E_e = 3,75\text{GeV}$, squares to $E_e = 2,0 \text{ GeV}$ and triangles to 1.0 GeV).

The hardening of spectra is observed with the increase in electron energy, but the maxima don't shift when the electron energy changes. This phenomenon occurs also in laminar medium, in which the maxima of spectra don't shift with the variation of particle Lorentz-factor. It is clearly seen that the E-dependence of photon number for photons up to 25 KeV is weaker than for photons of $\hbar\omega > 25 \text{ KeV}$ and the higher the photons energy, the more diverge the spectra. This is well illustrated in Fig.10, where the dependences of the total photon number on the electron energy is given in (5 ÷ 25) KeV frequency range (blank circles) and (25 ÷ 125) KeV (dark circles).

In the first case the plateau is reached already at 2GeV, while in the second case plateau is not reached at all at our energies. Thus, the total number of photons in an energy interval from several to 20 KeV depends on the energy of primary particles weaker, than the number of harder photons. This result

is very important and is to be taken into account when developing particle detectors.

The efficiency of transition radiation generation was studied at three density values of 1 cm thick styrofoam: $0,025\text{g/cm}^3$; $0,044\text{g/cm}^3$; $0,06 \text{ g/cm}^3$ and the electron energy of 3 GeV. The styrofoam blocks of density $0,06 \text{ g/cm}^3$ and $0,09 \text{ g/cm}^3$ were obtained by the compression of $0,04 \text{ g/cm}^3$ dense styrofoam and we can assume, that the thicknesses of partitions remained unchanged. The radiation spectra in these radiators are given in Fig. II. Blank figures denote proportional counter data, dark figures denote NaJ(Tl) data. Circles correspond to $\rho = 0,09 \text{ g/cm}^3$, squares to $\rho = 0,04 \text{ g/cm}^3$ and triangles to $\rho = 0,025 \text{ g/cm}^3$.

The spectra are seen to grow harder with the increase of density, the soft part of spectra ($\hbar\omega < 20 \text{ KeV}$) being almost unchanged when the density varied from $0,04 \text{ g/cm}^3$ to $0,09 \text{ g/cm}^3$. In the hard photon region the noticeable difference is marked between spectra at various densities. The hardening of spectrum with the increase of density can be explained first, by the increase of soft photon absorption and second, the dimensions of the pores become, apparently, too small the photons of low frequency (see formula (3)) to generate effectively. Here, also, good lacing of spectra as measured by two techniques is observed. Unlike other spectra, the spectrum for $\rho = 0,025$ has a dip in the region of lacing, that could be explained by statistical errors.

In Fig.12 the total number of photons as a function of styrofoam density both in (5 ÷ 25) KeV frequency range (blank circles) and in (25 ÷ 125) KeV frequency range (dark circles) is given.

One sees that in the first case a noticeable decrease of the degree of photon number growth takes place for higher densities, but in the second case such a saturation is not observed.

Thus, at $\gamma = 6 \cdot 10^3$ the number of transition photons grows with density up to the value of 0.09 g/cm^3 . We regret to add, that we lack any data with higher density radiators to continue this dependence to higher density region. But one could assert, that the selection of styrofoam radiator has to be made by the maximum of radiation generation. The spectra of transition radiation for different lengths of styrofoam radiator are shown in Fig. 13. The portion of hard photons is seen to increase with the increase in styrofoam thickness. This effect is explained by the more intense absorption of soft photons in comparison with the hard photon absorption.

In Fig. 14 the dependence of photon number N on the thickness of styrofoam in the range $(5 \div 25) \text{ KeV}$ (blank circles) and $(25 \div 125) \text{ KeV}$ (dark circles) are given.

The total number of photons is seen to grow lineary in $(25 \div 100) \text{ KeV}$ range with styrofoam thickness at least up to $l = 10 \text{ cm}$, followed by the slowing-down of its growth. In the soft photon region the slowing-down occurs comparatively earlier.

It follows from the comparison of transition spectra for laminar and porous radiators, that they are identical except the interference in the first case under certain conditions ^{4,5,6}.

In conclusion the author wishes to thank Prof. A.I. Alikhanian, A.Ts. Amatuni and S.G. Matinian for support, G.M. Garibian for helpful discussions.

FIGURE CAPTIONS

- Fig. 1. Transition Radiation Events as Detected in Streamer Chamber with Xe Admixture.
- Fig. 2. Spectral Distributions of Transition Radiation in Al Foil Radiator in $(5 \div 20) \text{ KeV}$ Frequency Range
 $(5 \div 20) \text{ KeV}$ a) $l = 1 \text{ mm}$, b) $l = 0.5 \text{ mm}$, c) $l = 0.25 \text{ mm}$
 d) $l = 1 \text{ mm}$, e) $l = 0.05 \text{ mm}$.
- Fig. 3. Spectral Distribution of Transition Radiation in Al Foil Radiator in $(20 \div 100) \text{ KeV}$ Frequency Range.
 1) $l = 1 \text{ mm}$ 2) $l = 0.5 \text{ mm}$ 3) $l = 0.25 \text{ mm}$ 4) $l = 0.1 \text{ mm}$
 5) $l = 0.05 \text{ mm}$.
- Fig. 4. The Total Photon Number in Al Foil Radiators as a Function of Foil Spacing in $(5 \div 20) \text{ KeV}$ and $(20 \div 100) \text{ KeV}$ Frequency Ranges.
- Fig. 5. Spectra of Transition Radiation in Organic Foil Radiator ($\text{Cl} - 44\%$, $\text{S} - 6.5\%$, $\text{C} - 42\%$, $\text{H} - 7.7\%$) for Different Number of Foils.
- Fig. 6. Transition Radiation Spectra in Organic Foil Radiator at Different Electron Energies.
- Fig. 7. E_e -Dependence of the Total Photon Number for Organic Foil Radiator.
- Fig. 8. Spectral Distribution of Radiation in Paper Sheet Radiator at $E_e = 680 \text{ MeV}$.
- Fig. 9. Radiation Spectra in Styrofoam of Density 0.04 g/cm^3 at Different Electron Energies.
- Fig. 10. E_e -Dependence of Total Photon Number.
- Fig. 11. Transition Radiation Spectra in Styrofoam at Different Densities.

Fig.12. Total Photon Number as a Function of Styrofoam Density.

Fig.13. Transition Radiation Spectra in Styrofoam of Density

$$\rho = 0.04 \text{ g/cm}^3 \text{ for Different Lengths of Radiator.}$$

Fig.14. Total Photon Number as a Function of Styrofoam Length.

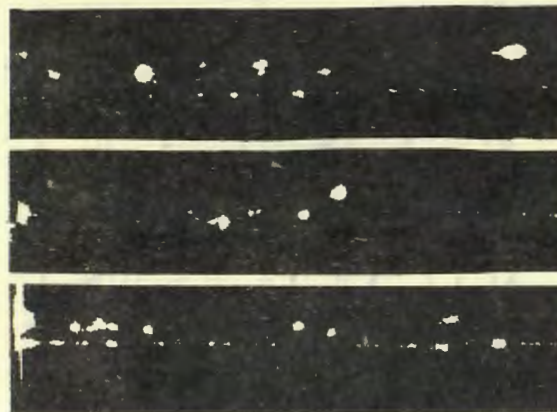


Fig. 1.

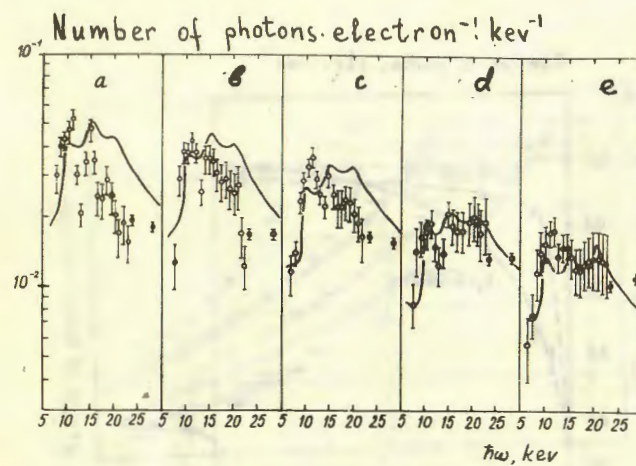


Fig.2.

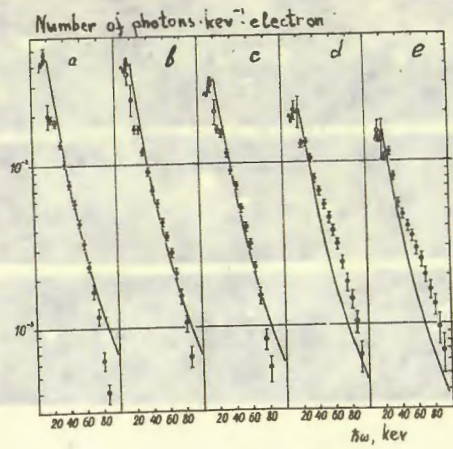


Fig. 3.

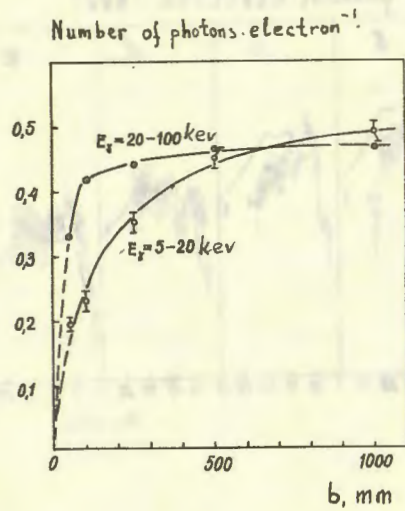


Fig. 4

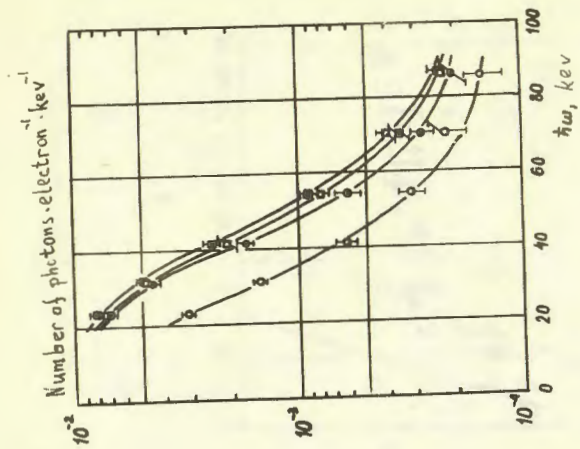


Fig. 6

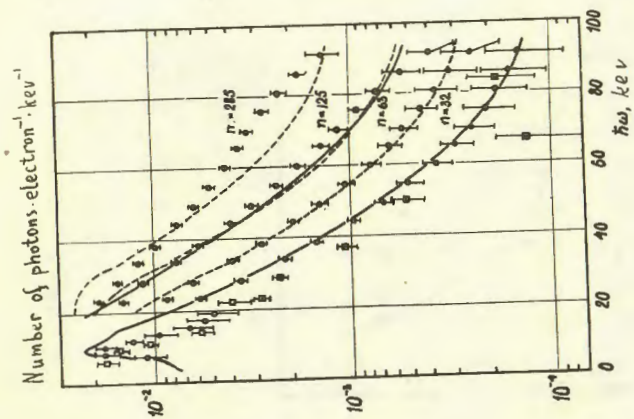


Fig. 5

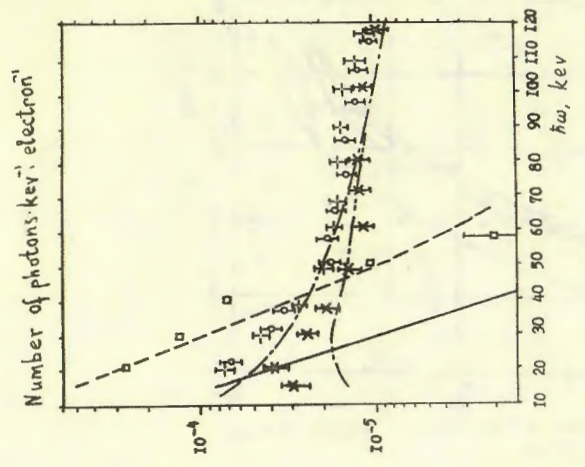


Fig. 8

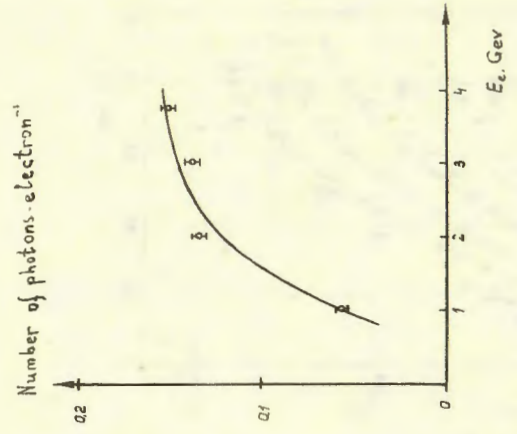


Fig. 7

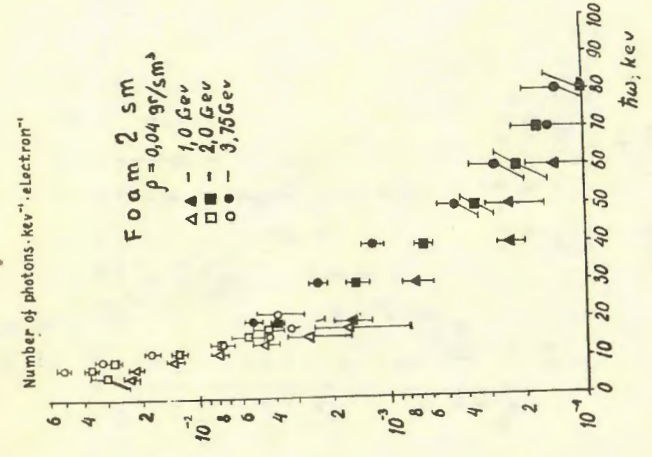


Fig. 9

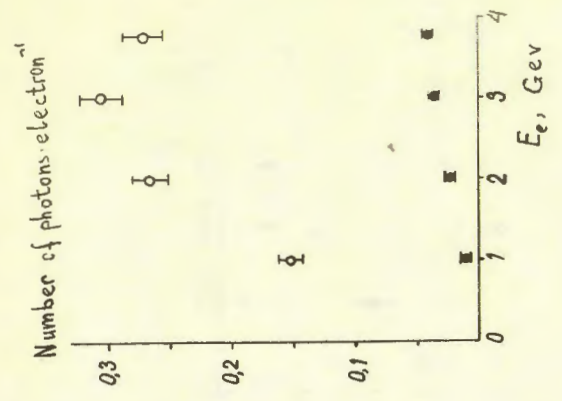


Fig. 10

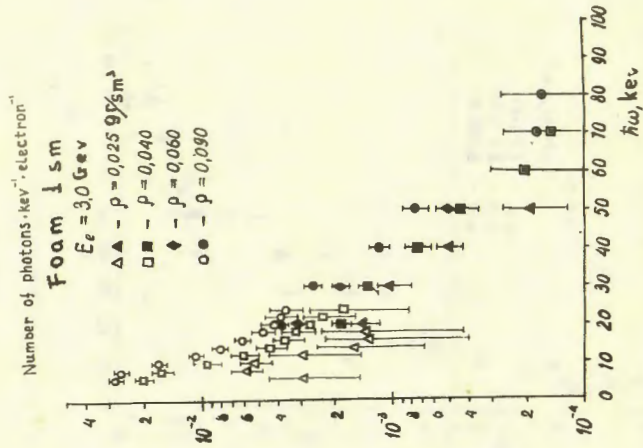


FIG. 11

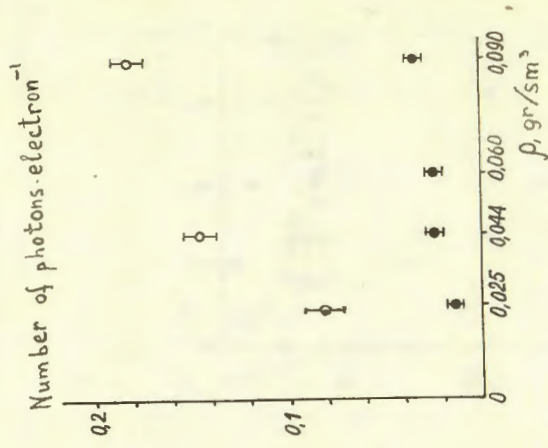


FIG. 12

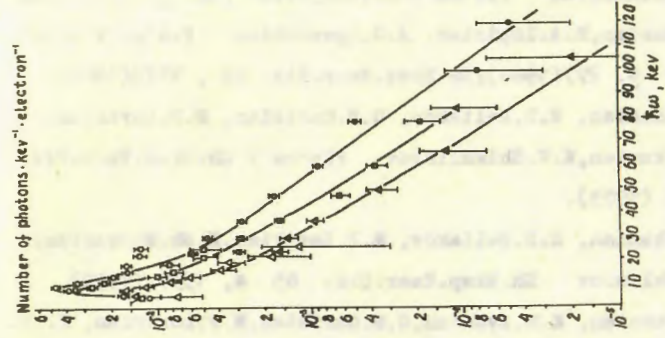


FIG. 13

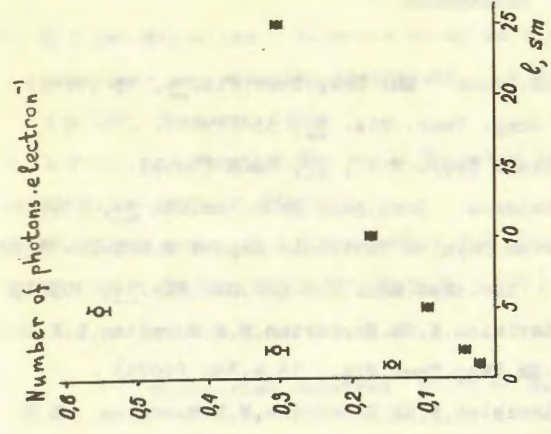


FIG. 14

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