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BREMSSTRAHLUNG SPECTRA IN AN INFINITE SODIUM IODIDE CRYSTAL

C. D. Zerby
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ABSTRACT

The calculated average Bremsstrahlung spectra resulting from one collision of a source photon in an infinite sodium iodide crystal are presented in graphical form. The data presented includes source photon energies from 0.1 to 20 $m_o c^2$.

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INTRODUCTION

One of the factors that may significantly affect the response of a sodium iodide crystal to incident gamma rays is the loss from the crystal of secondary bremsstrahlung radiation. In order to provide basic information from which this effect can be estimated, the average energy spectra of the bremsstrahlung radiation resulting from an incident photon which has had one interaction have been calculated from incident photon energies from 0.1 to 20 $m_o c^2$.

When a photon of sufficiently high energy makes a collision in sodium iodide, electrons can be ejected by the photoelectric or compton effect or an electron and a positron can be ejected by the pair production process. The ejected electrons and positrons slow down by making inelastic collisions with the bound electrons of the atoms or by radiative collisions with the electric fields of an atomic nuclei. Knowing the spectrum of the bremsstrahlung radiation from a radiative collision by an electron, one can calculate the total spectrum expected from the complete slowing-down process. The total spectrum can then be averaged over the velocity distribution of the electrons ejected by the incident photon. The result is then the average bremsstrahlung spectrum from electrons ejected by an incident photon which has made one collision.

The bremsstrahlung spectrum from an electron slowing down in sodium iodide has been previously calculated[1] using the Born approximation. The results of that calculation are repeated in Fig. 1 for convenience. It should be noted that the calculation just referred to did not take into account straggling effects but used a continuous slowing-down model for the electron degradation process and assumed the degradation occurred predominantly by inelastic collisions.

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1. C. D. Zerby and H. S. Moran, Bremsstrahlung Spectra in NaI and Air, ORNL-2454 (1958).

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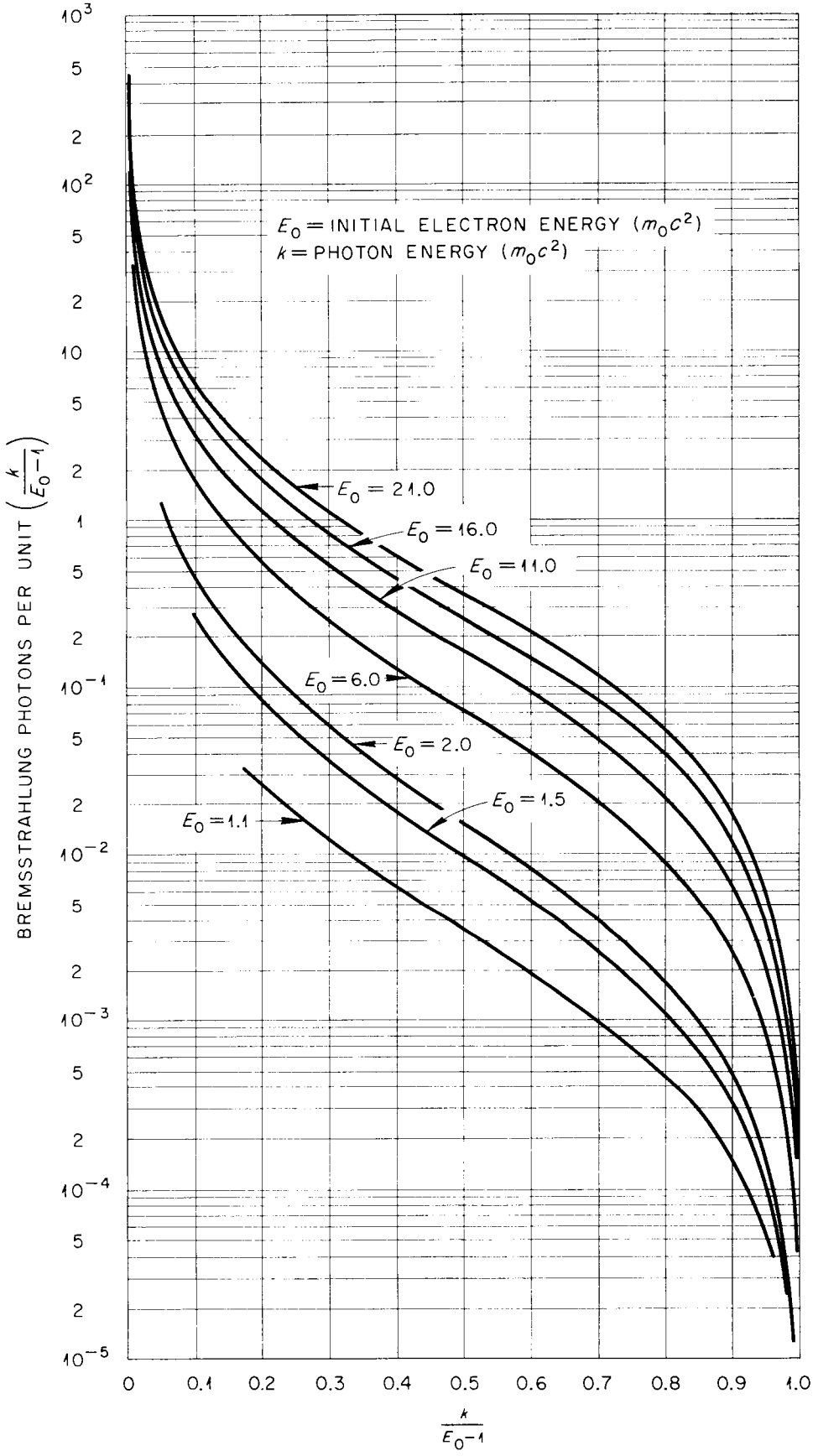

Fig. 1. Bremsstrahlung Spectra from an Electron Slowing Down in an Infinite Medium of Sodium Iodide.

METHOD OF CALCULATION

In the following discussion, all energies referred to will be in units of $m_o c^2$, the electron rest mass energy. In order to obtain the average bremsstrahlung spectrum per collision of an incident photon in sodium iodide it is necessary to calculate the following three quantities:

$K(E_1,k)$ = average number of bremsstrahlung photons produced per unit energy at energy k per photoelectric event of an incident photon with energy E_1,

$P(E_1,k)$ = average number of bremsstrahlung photons produced per unit energy at energy k per pair production event of an incident photon with energy E_1,

$G(E_1,k)$ = average number of bremsstrahlung photons produced per unit energy at energy k per compton event of an incident photon with energy E_1.

If the data given in Fig. 1 are represented by the function

$F(E_o,k)$ = average number of bremsstrahlung photons produced per unit energy at energy k resulting from an electron slowing down from initial energy E_o in sodium iodide (E_o is the total electron energy including rest mass energy),

then one immediately recognizes that

$$K(E_1,k) \equiv F(E_1 + 1,k). \tag{1}$$

The function $P(E_1,k)$ is easily obtained from

$$P(E_1,k) = \int_{E_o=k+1}^{E_1-1} \frac{2}{\sigma_p(E_1)} \frac{d\sigma_p(E_1,E_o)}{dE_o} F(E_o,k)dE_o \tag{2}$$

where $d\sigma_p/dE_o$ is taken to be the Bethe-Heitler differential cross section for producing either an electron or positron per unit energy at E_o and

σ_p is the total pair production cross section. For convenience, the Hough[2] approximations for these quantities were used and are given by

$$(3) \quad \frac{d\sigma_p(E_1, E_o)}{dE_o} = \Phi Q y \left[1 + 0.135(Q - 0.52)y(1 - y^2)\right](E_1 - 2)^{-1} \text{ for } E_1 > 2$$

where

$$y = 2\left[x(1 - x)\right]^{1/2},$$

$$x = \frac{E_o - 1}{E_1 - 2},$$

$$Q = (1 - \gamma)\left[\frac{1}{3}(4 - \gamma^2)(L - 1) - \gamma^2\alpha(\alpha - 1) - \gamma^4\alpha(L - \alpha)\right],$$

$$\gamma = \frac{2}{E_1},$$

$$L = \frac{2}{(1 - \gamma^2)} \operatorname{Ln}\left(\frac{E_1}{2}\right),$$

$$\alpha = \frac{1}{(1 - \gamma)^{1/2}} \operatorname{Ln}\left[\frac{E_1}{2} + \left(\frac{E_1^2}{4} - 1\right)^{1/2}\right],$$

$$\Phi = \frac{z^2}{137}\left(\frac{e^2}{m_o c^2}\right)^2.$$

In Eq. 3 the second term in the square brackets is dropped when it becomes negative, that is, when $E_1 \leq 4.2$. Integrating Eq. 3 over the range of E_o from 1 to $E_1 - 1$ gives the total pair production cross section

---

2. P. V. C. Hough, Phys. Rev. 73, 266 (1948).

$$(4)\qquad \begin{cases} \sigma_p(E_1) = \Phi\left[0.776Q + 0.0180Q^2\right] & 4.2 \geq E_1 \\ \sigma_p(E_1) = 0.785\Phi Q & 2 \leq E_1 \leq 4.2 \end{cases}$$

The numerical integration of Eq. 3 was performed and the results are presented in Fig. 2.

The function $G(E_1,k)$ is obtained from

$$(5)\qquad G(E_1,k) = \int_{E_o=k+1}^{(2E_1^2/1+2E_1)+1} \frac{1}{\sigma_c(E_1)} \frac{d\sigma_c(E_1,E_o)}{dE_o} F(E_o,k)dE_o$$

where $d\sigma_c/dE_o$ is the differential cross section for ejecting an electron per unit energy at energy E_o by a compton event and σ_c is the total compton cross section. These quantities are given by

$$(6)\qquad \frac{d\sigma_c(E_1,E_o)}{dE_o} = \pi r_e^2 \frac{1}{E_1^2}\left\{\frac{E_1}{E_2} + \frac{E_2}{E_1} + \frac{(E_o - 1)}{E_1E_2}\left[\frac{(E_o - 1)}{E_1E_2} - 2\right]\right\}$$

where

$E_2 = E_1 - E_o + 1,$

r_e^2 = classical electron radius,

and

$$(7)\qquad \sigma_c = \frac{\pi r_e^2}{E_1^3(1 + 3E_1)^2}\left[4(1 + E_1)^2(1 + 2E_1)E_1 + (1 + 2E_1)^2(E_1^2 - 2E_1 - 2)\right.$$

$$\left. \times\ LN(1 + 2E_1) - 2E_1^3(1 + 3E_1)\right].$$

The results of the numerical integration of Eq. 5 are presented in Fig. 3.

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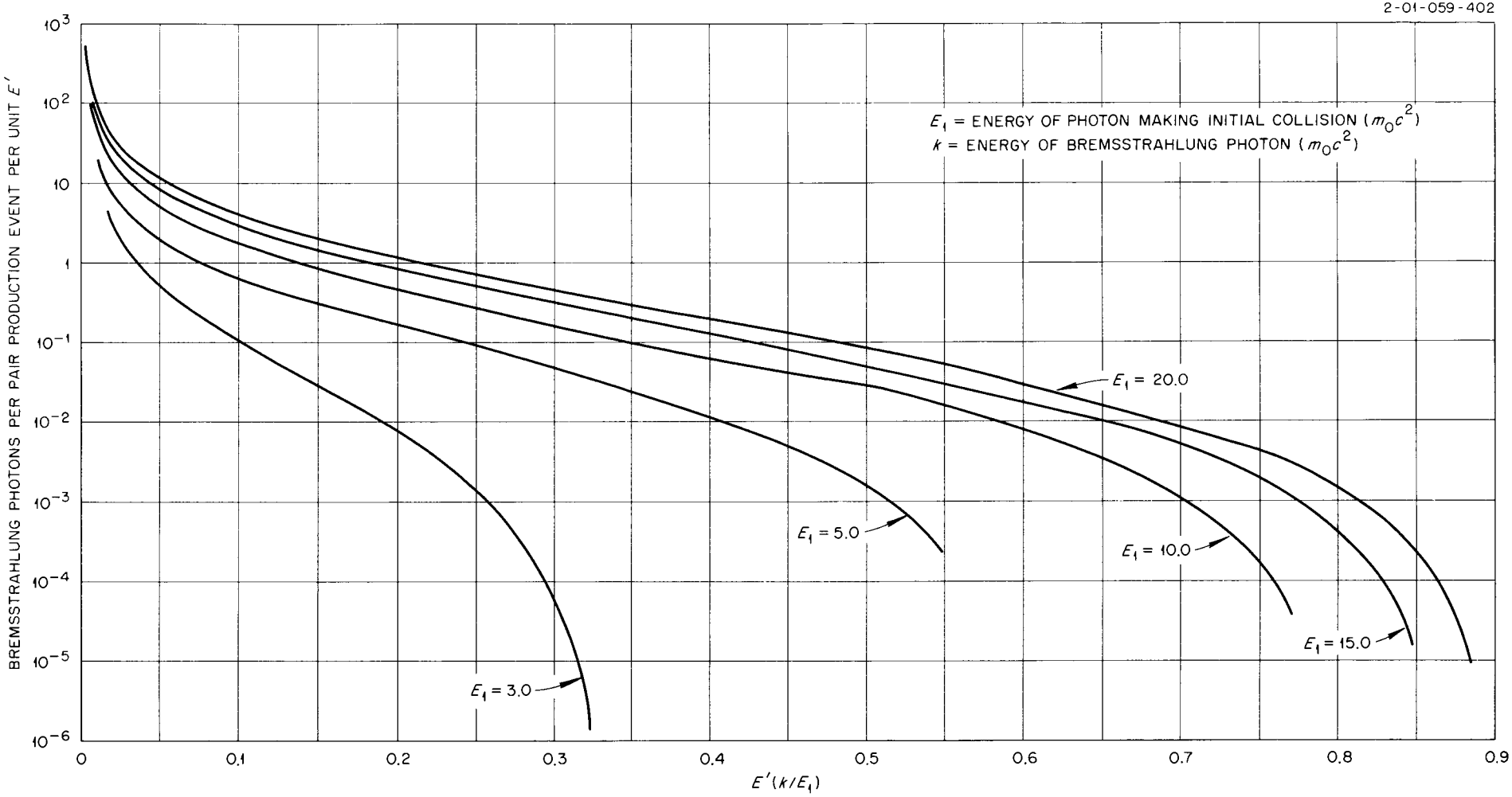

Fig. 2. Average Bremsstrahlung Spectro Produced per Pair Production Event of an Incident Photon with Energy E_1 in an Infinite Medium of Sodium Iodide.

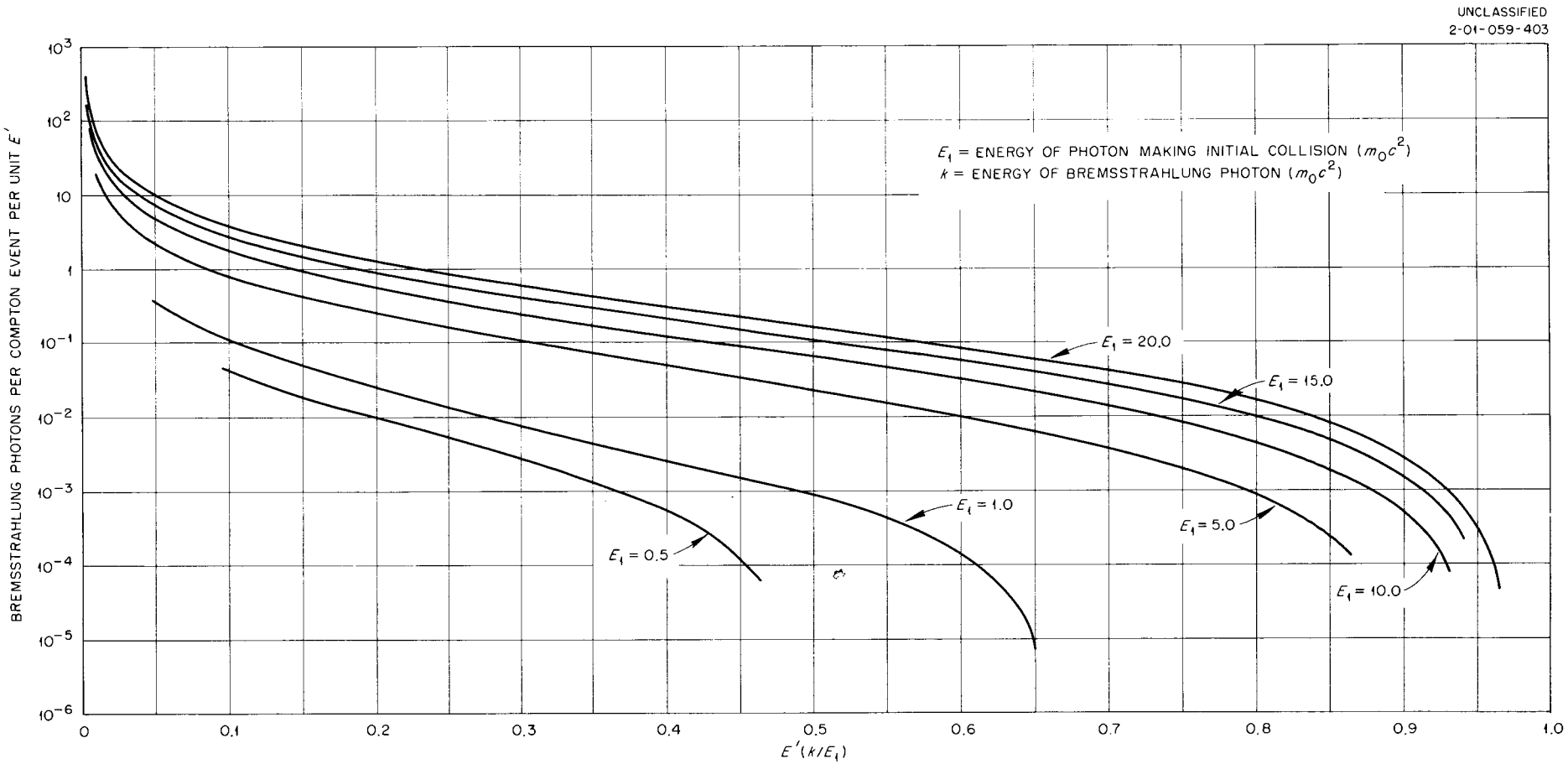

Fig. 3. Average Bremsstrahlung Spectra Produced per Compton Event of an Incident Photon with Energy E_1 in an Infinite Medium of Sodium Iodide.

If the average bremsstrahlung spectrum per collision of an incident photon is defined by the function

$T(E_1,k)$ = average number of bremsstrahlung photon produced per unit energy k per collision of an incident photon with energy E_1 in sodium iodide,

then this function can be determined by

$$T(E_1,k) = \frac{\Sigma_{ph}(E_1)K(E_1,k) + \Sigma_p(E_1)P(E_1,k) + \Sigma_c(E_1)G(E_1,k)}{\Sigma_{ph}(E_1) + \Sigma_p(E_1) + \Sigma_c(E_1)} \tag{8}$$

where $\Sigma_{ph}(E_1)$, $\Sigma_p(E_1)$ and $\Sigma_c(E_1)$ are the cross sections per molecule of sodium iodide for the photoelectric effect, pair production and compton scattering, respectively. Table 1 gives the values of these cross sections determined from data given by Grodstein,[3] and the results of the calculation of Eq. 8 are presented in Fig. 4.

Table 1. Gamma-Ray Cross Sections in Sodium Iodide

	Cross Section (barns/molecule)			
E_1 (m_oc^2)	$\Sigma_{ph}(E_1)$, Photoelectric Effect	$\Sigma_p(E_1)$, Pair Production	$\Sigma_c(E_1)$, Compton Scattering	Total
0.1	2366	0	35.75	2402
0.5	31.6	0	24.13	55.43
1.0	3.75	0	18.35	22.10
5.0	0.205	1.153	8.271	9.629
10.0	0.079	3.326	5.229	8.634
15.0	0.053	4.746	3.974	8.773
20.0	0.040	5.883	3,225	9.148

3. G. W. Grodstein, X-Ray Attenuation Coefficients from 10 kev to 100 Mev, NBS Circular 583 (1957).

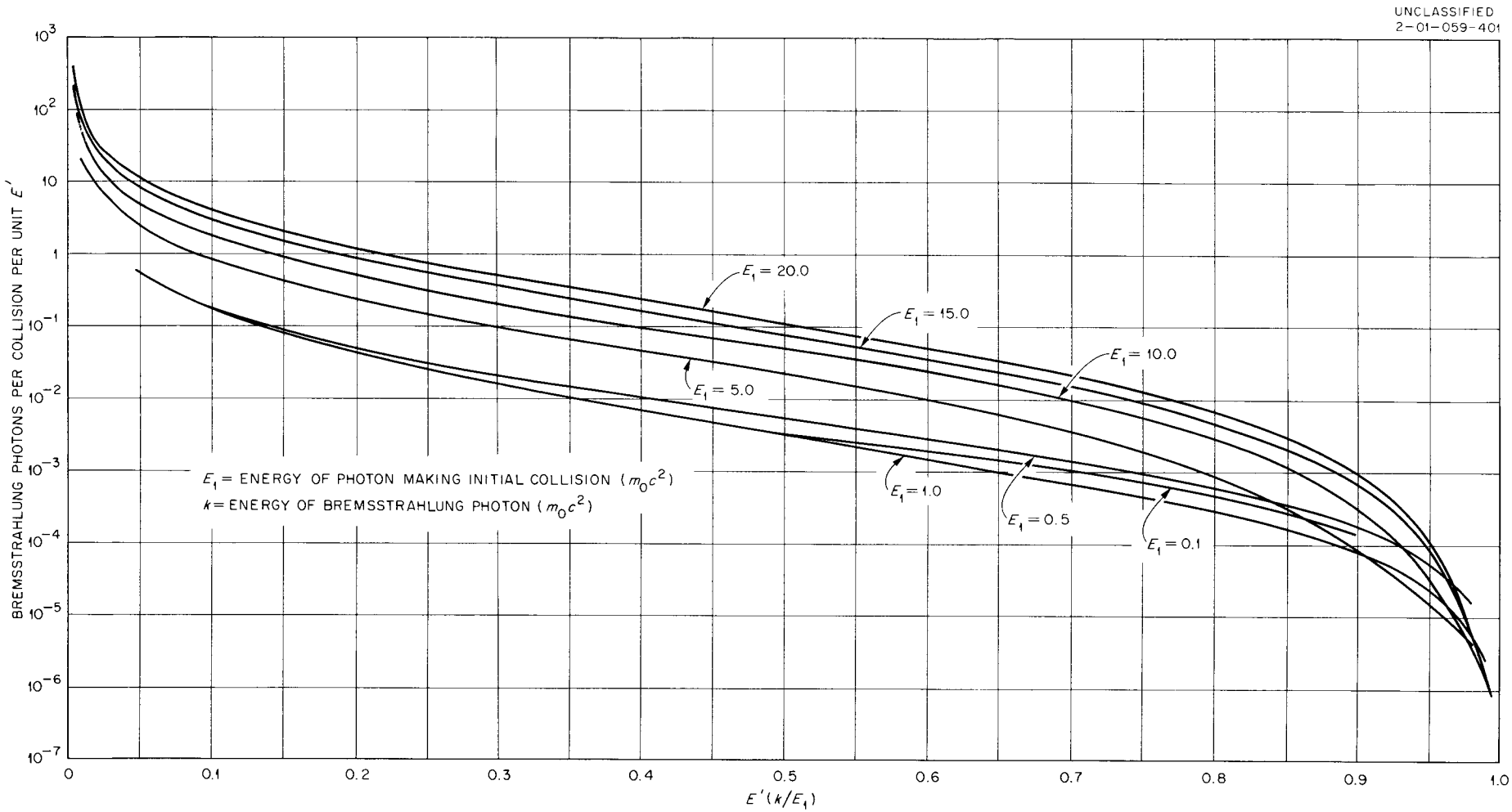

Fig. 4. Average Bremsstrahlung Spectra Produced per Collision of an Incident Photon with Energy E_1 in an Infinite Medium of Sodium Iodide.

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