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Cosmic Antimatter Annihilation
and the γ-Ray Background Spectrum

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ABSTRACT:

We present here some initial results of a detailed calculation of the cosmological γ-ray spectrum from matter-antimatter annihilation in the universe. The similarity of the calculated spectrum with the present observations of the γ-ray background spectrum above 1 MeV suggests that such observations may be evidence of the existence of antimatter on a large scale in the universe. Quantitative comparison of the calculations with the existing observations indicates that the product of interacting matter and antimatter densities at present is $\tilde{n}_{p,0}\,\tilde{n}_{\bar{p},0} \simeq 4 \times 10^{-26}$ cm^{-6}.

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The question of the existence of antimatter on a cosmological scale is one of the most basic problems of physics and cosmology. Recently it has taken on added interest because of the suggested possible role of antimatter in galaxy formation and the evolution of the universe (Alvén, 1965 ; Harrison, 1967 ; Omnès, 1969). It has long been recognized that the most promising way to search for evidence of antimatter on a cosmological scale is to attempt to observe γ-rays of cosmic origin which would be produced by the decay of neutral pions arising from matter-antimatter annihilation. In order to determine the annihilation-origin of such γ-rays, one must first calculate the γ-ray spectrum which would be produced by such annihilations so that the calculated spectrum may be compared with observational data on the γ-ray background spectrum for possible identification.

Because of their possible significance, we present here the results of such a detailed calculation, the details of which will be presented in full in a future article.

The cross sections for H-$\bar{H}$, p-$\bar{p}$, p-$\bar{H}$, and H-$\bar{p}$ annihlation as a function of temperature for "low temperatures" ($T < 10^{11}K$) have been included in the calculation. They are based on the recent calculations of Morgan and Hughes (1970) and are shown in Figure 1. Our calculations also include the effects of γ-ray absorption by pair production interactions with the intergalactic medium and photon transport by Compton interactions of the γ-rays with the intergalactic medium at high redshifts.

As can be seen in figure 1, the annihilation cross sections as a function of relative velocity can be expressed in various energy regions as a power law of the form

$$\sigma_A(v) = \sigma_i \left(\frac{v}{c}\right)^{-\delta_i} \tag{1}$$

where i = 1,2,3 and where

$\sigma_1 = 4.8 \times 10^{-26}$ cm^2 , $\delta_1 = 1$, for $10^{11}\,K \lesssim T \lesssim 10^{13}K$

$\sigma_2 = 2.2 \times 10^{-27}$ cm^2 , $\delta_2 = 2$, for $10^{4}\,K \lesssim T \lesssim 10^{11}K$

and $\sigma_3 = 2.6 \times 10^{-18}$ cm^2 , $\delta_3 = 0.64$, for $10\,K \lesssim T \lesssim 10^{4}\,K$

If $G_A(E_\gamma)$ is defined as the source spectrum of γ-rays from the decay of neutral pions produced by annihilation, the annihilation γ-ray <u>source</u> spectrum taking redshift effects into account and considering isotropic cosmological models (with the cosmological constant, Λ, set equal to zero) is given by

$$I_s(E_\gamma) = \left(\frac{c}{H_0}\tilde{n}_{p,0}\tilde{n}_{\bar{p},0}\right)\frac{\sigma_i c^{\delta_i}}{2\pi^{3/2}}\left(\frac{2k}{m_p}\right)^{\frac{1-\delta_i}{2}}\Gamma\left(2-\frac{\delta_i}{2}\right)\int dz\,[T(z)]^{\frac{1-\delta_i}{2}}\frac{(1+z)^2 G[(1+z)E_\gamma]}{(1+\Omega z)^{1/2}} \tag{2}$$

where H_0 is the Hubble constant, $\tilde{n}_{p,0}\tilde{n}_{\bar{p},0}$ is the product of the effective mean densities of <u>interacting</u> matter and antimatter protons at a redshift $z = 0$, T is the temperature of the interacting gas, k is Boltzmann's constant, Ω is the ratio of the average matter density in the universe at present to the critical density n_c =

$3H_0^2/8\pi G$ and $\Gamma(x)$ is the gamma function. In deriving equation (2) it is assumed that $\tilde{n}_p(z)\tilde{n}_{\bar{p}}(z) \sim (1+z)^6$. The matter temperature

$$T(z) \simeq \begin{cases} 2.7K\,(1+z) & \text{for } z \gtrsim 200 \\ 1.35\times10^{-2}K\,(1+z)^2 & \text{for } z \lesssim 200 \end{cases} \tag{3}$$

(Zeldovich, et al., 1969).

It can be shown that equations (2) and (3) together with the bounded form of the function $G_A(E_\gamma)$ yield source spectra of the form $E^{-\Gamma}$ as shown in table 1.

At high redshifts, when pair production and Compton scattering become important, it becomes necessary to solve a cosmological-photon-transport (CPT) equation in order to determine the γ-ray spectrum (Arons, 1971a,b). For a differential photon energy spectrum we find this equation to be of the form

$$y\frac{\partial I}{\partial y} + \epsilon\frac{\partial I}{\partial \epsilon} = 2I + y^2(y+\Psi)^{-1/2}\Big[\zeta A(\epsilon)I - \zeta\int_\epsilon^{b(\epsilon)} d\epsilon'\, B(\epsilon|\epsilon')I(\epsilon',y) - \frac{G(\epsilon)}{4\pi}\,\tilde{n}_{\bar{p},0}\,y^3\,\Phi(y)\Big] \tag{4}$$

where $I = I(\epsilon, y)$ is the annihilation γ-ray flux,

$y \equiv 1 + z$

$\epsilon \equiv E_\gamma/m_e c^2$

$\Psi \equiv (1-\Omega)/\Omega$

$\zeta \equiv 2.5 \times 10^{-2}\,\Omega^{\frac{1}{2}}$

The source function $G_A(E_\gamma)$ is taken from Stecker (1967).

The annihilation-rate function

$$\Phi(y) = \frac{\sigma_A[T(y)]}{\sigma_u} v[T(y)] \qquad (5)$$

where

$$\sigma_u = (\Omega n_e c)^{-1} H_0 \quad , \qquad (6)$$

The function $A(\epsilon)$ is proportional to the total cross section for absorption and scattering of γ-rays by pair production and Compton interactions. The scattering function $B(\epsilon|\epsilon')$ is proportional to the probability that a γ-ray of energy ϵ' will Compton scatter to energy ϵ. The upper limit

$$b(\epsilon) \equiv \begin{cases} \epsilon/(1-2\epsilon) & , \epsilon < \frac{1}{2} \\ \infty & , \epsilon \geq \frac{1}{2} \end{cases} \qquad (7)$$

The function $I_A(E_\gamma, y=1)/\tilde{n}_{p,0}\tilde{n}_{\bar{p},0}$, obtained by numerical solution of the CPT equation, is shown by the solid line in figure 2. If we chose a value for $\tilde{n}_{p,0}\tilde{n}_{\bar{p},0}$ of 4×10^{-26} cm^{-6} for the product of the mean densities of interacting matter and antimatter at present ($z=0$), we obtain a theoretical annihilation spectrum compatible in both form and intensity to the observed spectrum of cosmic background γ-radiation between 1 and 6 MeV (Vette, et al. 1970). We thus conclude that these observations may be evidence of the existence of antimatter on a cosmological scale. This conclusion, however, is subject to the following conditions:

(1) There must be an additional power-law background component of X-rays below 1 MeV of another origin. Our calculations of the annihilation γ-ray spectrum below 1 MeV (not presented in their entirety here) fall well below the observed power-law spectrum in that energy range.

(2) The peak in the calculated annihilation spectrum near 1 MeV is caused by absorption and scattering of the γ-rays by interactions with an intergalactic medium having an average density near the critical value n_c.

(3) There is strong evidence that at a redshift of $z \sim 2.5$ (or perhaps somewhat greater) the intergalactic medium is strongly ionized and equation (3) does not hold (Gunn and Peterson 1965, Rees 1969). At the redshift where reionization occurs there will be a rapid drop in the cross section for annihilation (see figure 1) resulting in a sharp steepening of the γ-ray spectrum at an energy $E_{\gamma,c} \sim 50$ MeV. Above $E_{\gamma,c}$ the spectrum will drop off much more rapidly than the power-law dependence $\sim E_{\gamma}^{-2.86}$ shown in figure 2. It is thus not expected to conflict with the upper limit on the isotropic background of $\sim 3 \times 10^{-5}$ $cm^{-2}sec^{-1}sr^{-1}$ for the integral flux above 100 MeV as reported by Clark, et al.(1970).

(4) The observational data on the γ-ray spectrum above 1 MeV do not provide enough information at present to yield a unique identification of their origin. There have been several alternative attempts to explain the background flux as being due to the decay of neutral

pions produced by cosmic-ray interactions at high redshifts (the protar hypothesis (Stecker 1969a,1969b,1971)), galactic electron bremsstrahlung (Rees and Silk 1970), extragalactic electron bremsstrahlung (Silk 1970) extragalactic proton bremsstrahlung (Brown 1970) and nuclear emission lines (Clayton and Silk 1969). More recent work shows that none of these alternatives except the protar hypothesis seems capable of explaining both the form and intensity of the observed flux (Vette, et al. 1970,Stecker,et al.1971; Stecker and Morgan 1971, Jones 1971). An observational test between the protar hypothesis and the annihilation hypothesis can be made at energies gies above 50 MeV. The annihilation hypothesis predicts a steepening in the background spectrum above 50 MeV whereas the protar hypothesis predicts a steepening the the spectrum at about 7 GeV(Fazio and Stecker 1970). Should future investigations indicate that the background γ-radiation above 1 MeV is not due primarily to matter antimatter annihilation, this will place an upper limit on the product $\tilde{n}_{p,0}\tilde{n}_{\bar{p},0}$ of the order of 10^{-26} cm^{-6}.

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Table 1

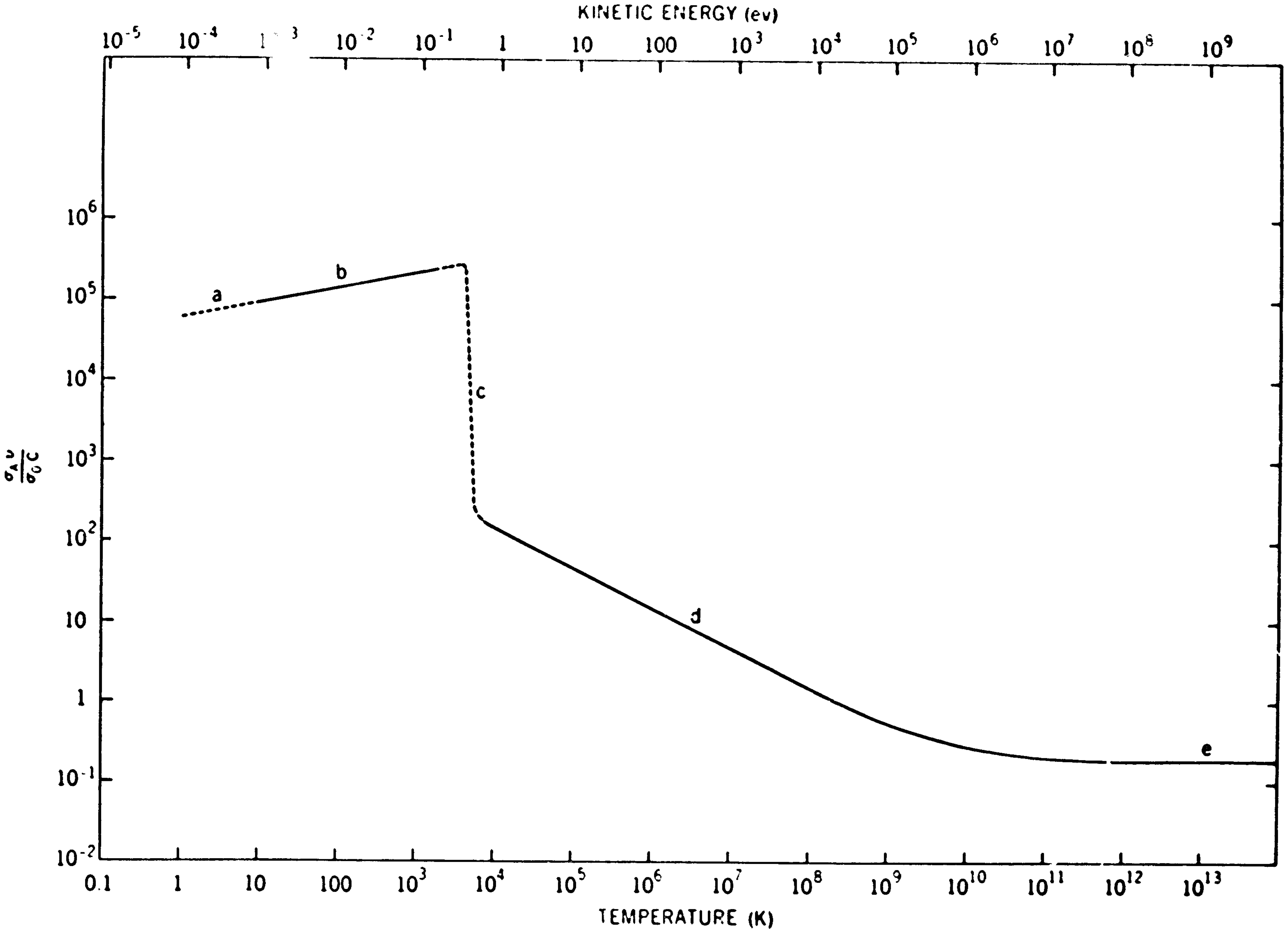
Exponents of the Cosmological Annihilation γ-ray Source Spectra

z	E_γ	δ	Γ	
0-150	500keV-70MeV	0.64	2.86 3.36	$(\Omega=1)$ $(\Omega \ll z^{-1})$
150-10^3	70keV-500keV	0.64	2.68 3.18	$(\Omega=1)$ $(\Omega \ll z^{-1})$
10^3-10^8	70keV	2	2.00 2.50	$(\Omega=1)$ $(\Omega$ [illegible]$^{-1})$

FIGURE CAPTIONS

Figure 1. Cross section times velocity for hydrogen-antihydrogen annihilation of nucleons as a sum for the interactions listed below integrated over a Maxwell-Boltzmann distribution at temperature T and taking ionization into account (Morgan and Hughes 1970). (a)$\sigma_{H\cdot\bar{H}}$ (extrapolated), (b)$\sigma_{H\cdot\bar{H}}$ (calculated),(c)$\sigma_{H\cdot\bar{H}}, \sigma_{p\cdot\bar{H}}, \sigma_{\bar{p}+H}$ multiplied by the appropriate factors to take account of fractional ionization, (d)$\sigma_{p\cdot\bar{p}}$ taking coulomb attraction into account, (e)$\sigma_{p\cdot\bar{p}}$ from high energy accelerator data. $\sigma_0 \equiv 2.5 \times 10^{-25}$ cm^2.

Figure 2. The cosmological γ-ray annihilation spectrum calculated by numerical solution of the CPT equation (equation (4)) for $\Omega = 1$. The solid line represents the complete solution. The other curves show the effect of neglecting the absorption and scattering terms in the CPT equation.


KINETIC ENERGY (ev)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
100
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
$\frac{\sigma_A v}{\sigma_0 c}$
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
a
b
c
d
e
0.1
1
10
100
10^{3}
10^{4}
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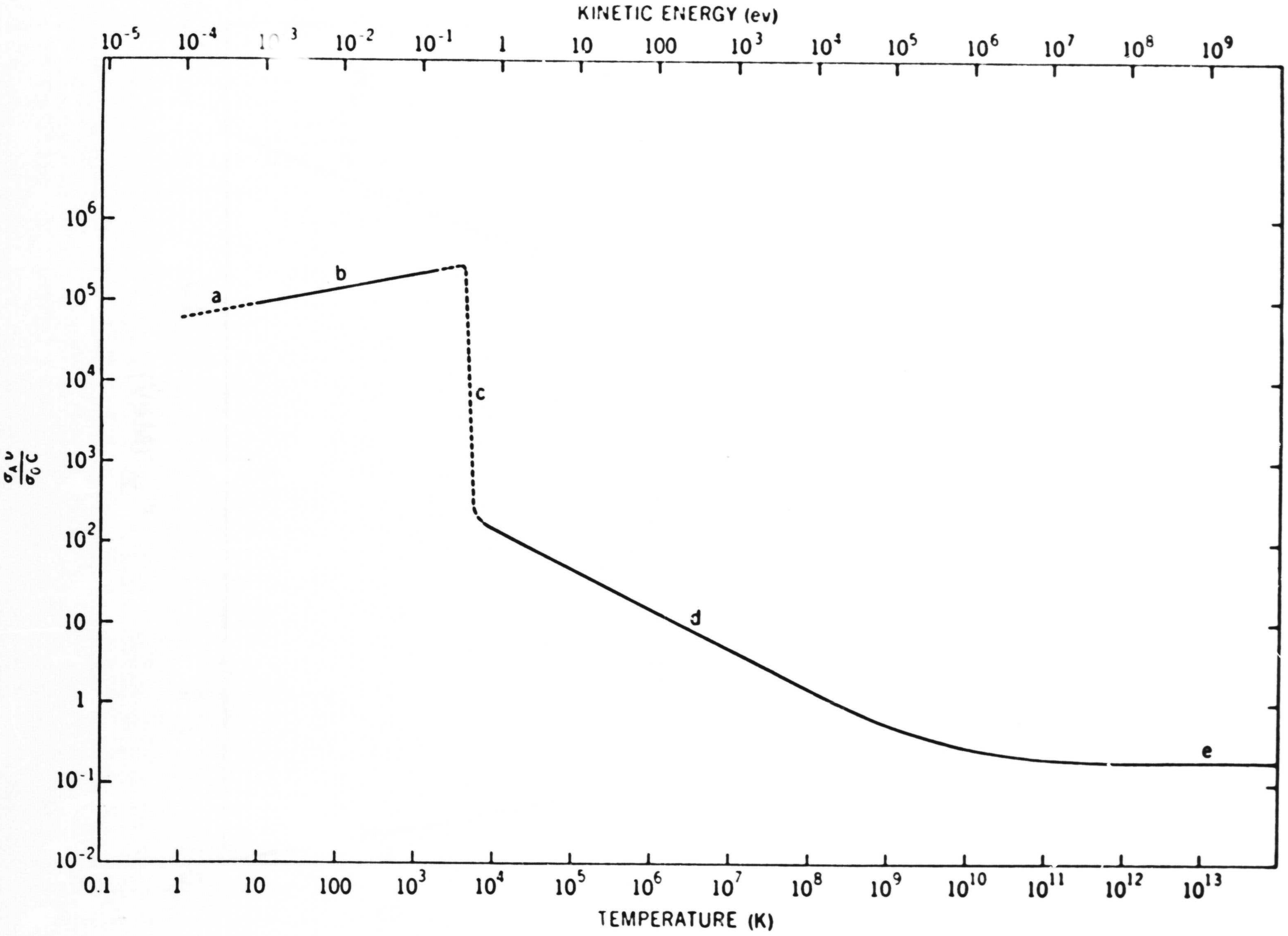
10^{12}
10^{13}
TEMPERATURE (K)


KINETIC ENERGY (ev)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
100
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
$\frac{\sigma_A v}{\sigma_0 c}$
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
a
b
c
d
e
0.1
1
10
100
10^{3}
10^{4}
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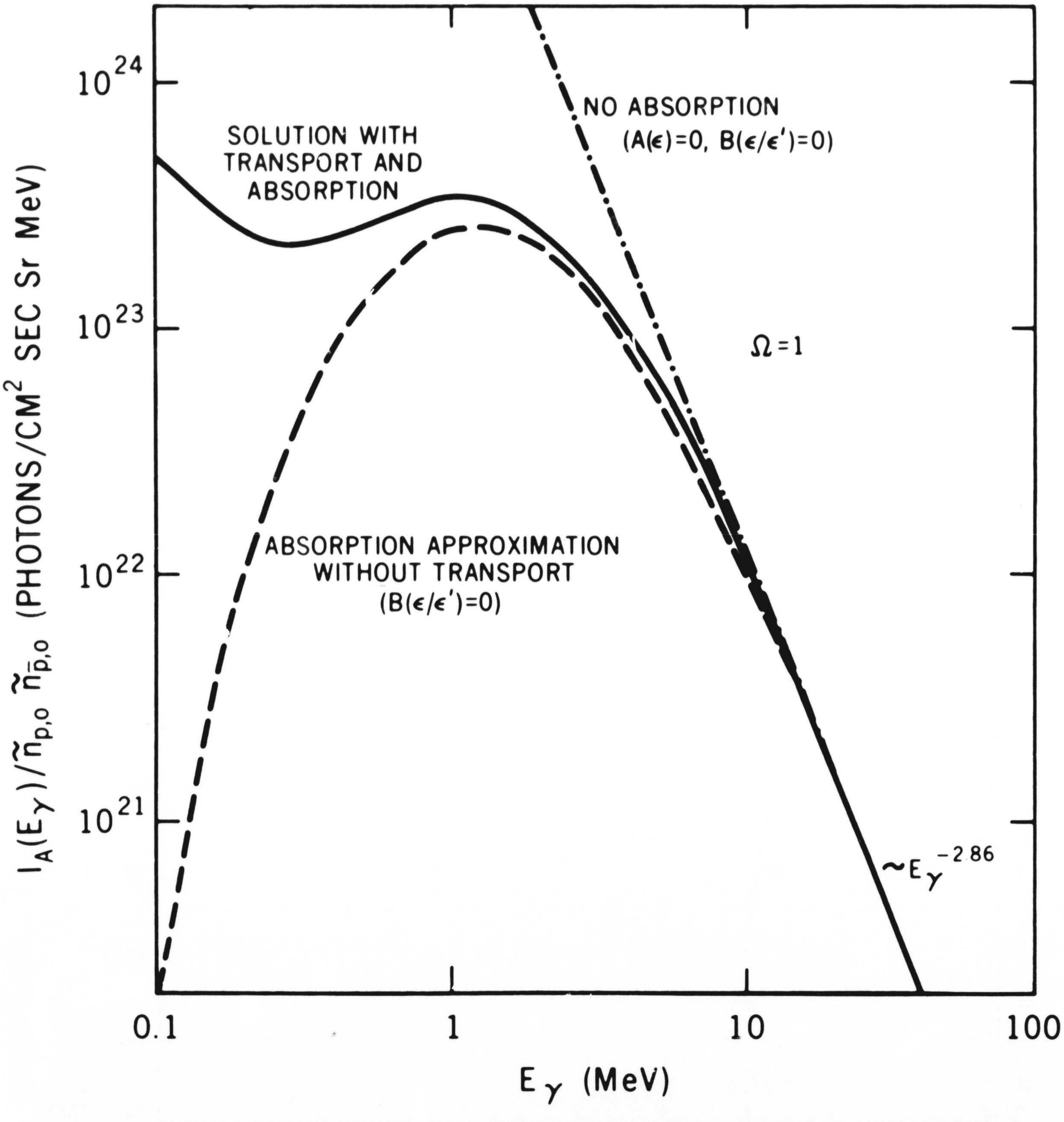
10^{12}
10^{13}
TEMPERATURE (K)


10^{24}
10^{23}
10^{22}
10^{21}
$I_A(E_\gamma)/\tilde{n}_{p,o}\,\tilde{n}_{\bar{p},o}$ (PHOTONS/CM^2 SEC Sr MeV)
0.1
1
10
100
E_γ (MeV)
SOLUTION WITH TRANSPORT AND ABSORPTION
NO ABSORPTION
$(A(\epsilon)=0,\ B(\epsilon/\epsilon')=0)$
$\Omega=1$
ABSORPTION APPROXIMATION WITHOUT TRANSPORT
$(B(\epsilon/\epsilon')=0)$
$\sim E_\gamma^{-2.86}$