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Astrophysical Implications of New Light Higgs Bosons

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ABSTRACT

We explore the consequences of the existence of a new light pseudoscalar particle, the Higglet or the axion. Thermal energy can be converted into Higglets through annihilation ($e^+e^- \to \gamma h$), photoproduction ($\gamma e \to he$), and plasma decay ($\gamma_p \to \gamma h$). Explicit expressions for the cross sections and decay lifetimes are given. We conclude that Higglet production can occur in advanced stages of stellar evolution and in the big bang creation of the universe. The most dramatic effect, however, is expected during gravitational collapse of massive stars where Higglets may help trigger a supernova explosion.

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It has been recently pointed out by S. Weinberg[1] and F. Wilczek[2] that a light pseudoscalar Higgs boson, called a Higglet or an axion, is a necessary consequence of theories[3] which unify the strong, weak and electromagnetic interactions and which possess a global U(1) chiral symmetry to naturally avoid CP violation in strong interactions.[4] Though reactor and beam dump experiments argue against such a particle,[1,5] so far the analysis of these experiments and of the nuclear reactions involving Higglets is too crude to definitely rule out their existence.[6] New experiments to search for Higglets have been proposed.[7,8]

Here we shall concentrate on the astrophysical implications of such light pseudoscalar mesons. In principle, Higglets could be created in three different astrophysical situations: during the big bang birth of the universe, during nuclear burning in stellar evolution, and in the final gravitational collapse of massive stars. We shall argue that within the range of parameters predicted for Higglets, they play a most interesting role in gravitational collapse.

In this context one naturally compares Higglets with photons and neutrinos: the semi-weak interaction between matter and Higglets implies that $\sigma_\gamma >> \sigma_h >> \sigma_\nu$, where σ_γ, σ_h and σ_ν are typical production and absorption cross sections for photons, Higglets and neutrinos (we shall be more precise below). Higglets have thus the potential to act <u>both</u> as a mechanism for energy transport <u>and</u> energy loss. Which role they play depends on the stellar structure of the Higglet emitting region.

We shall assume, for orientation, that $50\ \mathrm{KeV}/c^2 \leq m_h \leq 200\ \mathrm{KeV}/c^2$, and that the Higglet decays through $h \rightarrow \gamma\gamma$ with $0.01\mathrm{s} \leq \tau_h \leq 1\mathrm{s}$. The threshold temperature is $T_{threshold} = (m_h c^2)/k \approx (1\text{-}4) \times 10^9\,{}^\circ\mathrm{K}$. We shall consider the production of Higglets in pure leptonic processes for which exact expressions can be derived. The interaction Lagrangian is[1]

$$L_{int} = g\bar{\psi}_e \gamma_5 \psi_e h = 2^{\frac{1}{4}} G_F^{\frac{1}{2}} m_e c_e \bar{\psi}_e \gamma_5 \psi_e h \qquad (1)$$

where c_e =tan α or ctn α and is of order one. We will set $c_e = 1$ in numerical calculations.

We shall consider only three processes, shown in Fig. 1, for Higglet creation: (i) annihilation, (ii) photoproduction, and (iii) plasma decay.

i) for electron-positron annihilation, Fig. 1(a),

$$e^+ + e^- \rightarrow \gamma + h \quad , \qquad (2)$$

we find the following total cross section:

$$\sigma(e^+e^- \rightarrow \gamma h) = \frac{\alpha\, g^2}{2s\beta^2} \left\{ \left[1 + m_h^2/s - 2(m_h^2/s)(2m_e^2 - m_h^2)/(s-m_h^2) \right] \ln(\frac{1+\beta}{1-\beta}) - 2m_h^2 \beta/(s-m_h^2) \right\} \qquad (3)$$

where $\beta = (1-4m_e^2/s)^{\frac{1}{2}}$ and s is the square of the c.m. energy. This cross section is shown in Fig. 2 for $m_h = 50$ KeV/c^2. It depends very weakly on m_h. Assuming, as we have done, that $m_h < 2m_e$, we find that $\sigma(e^+e^- \rightarrow \gamma h)$ diverges like $\frac{1}{\beta}$ as $\beta \rightarrow 0$ near threshold where e^+e^- annihilate from rest.[9]

ii) Photoproduction of Higglets,

$$\gamma + e \rightarrow h + e \qquad (4)$$

is shown in Fig. 1(b). We find,

$$\sigma(\gamma e \to he) = \frac{\alpha g^2}{8s}\left(\frac{p}{k}\right)\Bigg\{-3 + m_e^2/s + 3m_h^2/(s-m_e^2) + m_e^2 m_h^2/s(s-m_e^2) + 4m_h^2(s + m_e^2)/(s-m_e^2)^2 + \left(\frac{\sqrt{s}}{p}\right)\Big[1 - 2m_h^2/(s-m_e^2) - 2m_h^2(2m_e^2 - m_h^2)/(s-m_e^2)^2\Big]\ln\left(\frac{p_0k_0+pk-m_h^2}{p_0k_0-pk-m_h^2}\right)\Bigg\} \quad (5)$$

where

$$p_0 = (s-m_e^2+m_h^2)/2\sqrt{s}, \quad p = (p_0^2-m_h^2)^{\frac{1}{2}}, \quad k_0 = (s+m_e^2)/2\sqrt{s}, \quad \text{and } k = \sqrt{s}-k_0 .$$

In Fig. 2 we have plotted $\sigma(\gamma e \to he)$ as a function of $s/4m_e^2$ for $m_h = 50$ KeV/c^2. Except near threshold, this cross section is not sensitive to the value of m_h.

iii) Plasma decay,

$$\text{Plasmon } (k) \to \gamma(k') + h \quad (6)$$

as shown in Fig. 1(c) is somewhat more difficult to calculate because of the loop integral. The final photon may also represent a plasma oscillation for which the four vector square k'^2 does not vanish. The amplitude is proportional to the three-point function

$$A_{\mu\nu}(k,k') = -2\int\frac{d^4\ell}{(2\pi)^4}\,\mathrm{Tr}\left\{\gamma_\mu G(\ell)\,\gamma_\nu G(\ell-k')\,\gamma_5 G(\ell-k)\right\} \quad (7)$$

where $G(\ell)$ is the Green's function for the propagation of an electron in the plasma.[10] We have evaluated this function for arbitrary k setting $k'^2 = 0$ and keeping only the free electron propagator in the Green's functions appearing in Eq. (7), i.e., $G(\ell) \to 1/(\not{\ell}-m_e)$, etc. We find

$$A_{\mu\nu}(k,k') = \epsilon_{\mu\nu\alpha\beta} k^{\alpha} k'^{\beta} A(k,k') \tag{8}$$

where A is in general a complex amplitude

$$A(k,k')\Big|_{\substack{k'^2=0\\ 2k\cdot k'=k^2-m_h^2}} = \frac{m_e}{\pi^2(k^2-m_h^2)}\{J(m_h^2/m_e^2) - J(k^2/m_e^2)\} \tag{9}$$

with

$$J(x^2) = \left\{\theta(1-x/2)\cos^{-1} x/2 + \theta(x/2-1)i\ \ln\left(x/2 + \sqrt{\frac{x^2}{4}-1}\right) - \pi/2\right\}^2 . \tag{10}$$

As expected, the imaginary part of A comes from $J(k^2/m_e^2)$ for $k^2>4m_e^2$.

Both longitudinal and transverse plasmon decay are allowed, and we find that the decay widths are

$$\Gamma_\ell = \tau_\ell^{-1} = \frac{\alpha^2 g^2 m_e^2}{3\pi^3 k^2(\partial\epsilon^\ell/\partial\omega)} (1 - m_h^2/k^2)\left|J(m_h^2/m_e^2) - J(k^2/m_e^2)\right|^2 \tag{11}$$

with a similar expression for $\Gamma_t = \tau_t^{-1}$ in which $k^2\partial\epsilon^\ell/\partial\omega$ is replaced by $\partial(\omega^2\epsilon^t)/\partial\omega$. Here $\omega=k_0$, and ϵ^ℓ and ϵ^t are the longitudinal and transverse dielectric constants[10] respectively.

What astrophysical processes are likely to be affected by Higglet production:

a) We do not expect much Higglet creation during normal stellar evolution, because temperatures range between 10^7 to 10^9 degrees Kelvin for hydrogen through carbon burning. Clearly for photoproduction and plasma decay we need $T \gtrsim T_{threshold}$. Though e^+e^- pairs have enough mass-energy to annihilate into Higglets, the number of such pairs is very small at low temperatures. In Fig. 3 we plot $R_h(T,\mu_e)$, the Higglet production rate per cm^3 per second, defined by

$$R_h(T,\mu_e) = \iint dn_{e^+}\ dn_{e^-}\ v\sigma(e^+e^- \to \gamma h) \tag{12}$$

where $\vec{v}$ is the relative velocity between e^+ and e^-, and

$$dn_{e\pm} = 2\{1 + \exp(E_\pm/kT \pm \mu_e/kT)\}^{-1} d^3p_\pm/(2\pi)^3$$

are the $e^\pm$ distribution functions for a given electron chemical potential μ_e. $R_h(T,\mu_e)$ is a very steep function of T. The ranges of T and μ_e shown in Fig. 3 describe the conditions during gravitational collapse which we shall treat separately. We expect, however, some Higglet production during the advanced stages of evolution in massive stars, namely oxygen through silicon burning when $T \approx (1{\cdot}5 - 3{\cdot}5) \times 10^9\,°K$. Higglet emission will speed up these processes because they transport energy much more readily than photons. We can find no observational consequences of this speed up.

It is interesting to note that above a certain temperature T^* neutrino production dominates over Higglet production because $\sigma_\nu \sim s$ and $\sigma_h \sim \frac{1}{s}$. For e^+e^- annihilation, $\sigma(e^+e^- \to \nu\bar{\nu}) \simeq G_F{}^2 s$ and $\sigma(e^+e^- \to \gamma h) \approx \alpha m_e{}^2 G_F/s$, and we can estimate T^* by requiring these two cross sections to be equal: $T^* = \frac{1}{k}\sqrt{s^*} = \frac{1}{k}\,(\alpha m_e{}^2/G_F)^{1/4} \approx 1{\cdot}3\times10^{12}\,°K$. In Fig. 3 we have also plotted the neutrino pair production rate per cm^3 per second,

$$R_\nu(T,\mu_e) = \iint dn_{e^+} dn_{e^-}\ v\sigma(e^+e^- \to \nu\bar{\nu}) \tag{13}$$

and we have summed over the three kinds of neutrinos ν_e, ν_μ and ν_τ[11]. Indeed we find that $R_\nu(T,\mu_e) > R_h(T,\mu_e)$ for $T \gtrsim 1{\cdot}3\times10^{12}\,°K$. For photoproduction, we estimate that $T^* \simeq 4{\cdot}5\times10^{12}\,°K$.

b) Such high temperatures are presumably encountered only during the very early stages of the expansion of the universe, in the so-called hadron era about which not much is known. Assuming the standard big bang theory, Higglets were present in large numbers and were as plentiful as photons with which they were in thermal equilibrium. The subsequent evolution of the Higglet gas depends on the interaction strength, mass and lifetime of the Higglet. Given our earlier assumptions about these properties, we can say that the Higglets decayed sometime after the neutrinos decoupled from matter ($T \approx 10^{11}\,°K, t_{expansion} \approx 10^{-2}s$), but probably before e^+e^- annihilation stopped ($T \approx 10^9\,°K$, $t_{expansion} \approx 10^2 s$). In this case the only observable effect would be a distortion of the present 2·7°K blackbody radiation. However, since the decay occurred very early, the decay photons would have completely thermalized, that is the fluctuation in the radiation field caused by Higglet decay in such early times is quickly washed out.[12]

c) Higglet production during gravitational collapse is a most promising mechanism for triggering supernova explosions. Occurring in the temperature range $T \approx 10^{10} - 10^{11}\,°K$, well above threshold yet not high enough for the neutrinos to dominate, conversion of thermal energy into Higglets proceeds via all of the three reactions discussed above. In this temperature range which corresponds to $s/4m_e^2 \approx .7\text{-}70$, we have seen that these reactions have rather large cross sections, $10^{-35} - 10^{-36}\,cm^2$, so the energy conversion proceeds rapidly. The deposition of this energy into the material around the imploding core can help blow-off the envelope.[13]

The following scenario seems plausible: much of the gravitational binding energy of the core is still carried away by neutrinos from neutronization, however a few percent is turned into heat as the core collapses. This thermal energy is converted into ν-$\bar{\nu}$ pairs and into Higglets by e^+e^- annihilation, photoproduction and plasma decay. The ν-$\bar{\nu}$ escape readily, within .1 to 1 second, but the Higglets slowly diffuse out (our estimates range between 1 to 10 hours). While the neutrinos pass through the envelope with very few interactions, the Higglets deposit almost all their energy in the extended envelope either by direct absorption or through their decay photons which of course are readily absorbed in the envelope. We estimate that about 10^{50} ergs can be transported by Higglets and deposited in the envelope.

This is a crude estimate for a very simple scenario, however the advantages and disadvantages of the Higglet over the neutrino in triggering supernova explosions are clear: neutrinos carry away energy promptly from the hot dense core, but deliver very little of it to the envelope. Higglets, on the other hand, by decaying into photons deposit all their energy inside the envelope, but take a relatively long time to diffuse out of the core.

One can easily list other reactions for Higglet production, however we doubt that these will change the basic picture emerging from our analysis: the existence of a Higglet would have a small effect on big bang theories and on stellar evolution, but would have dramatic consequences during gravitational collapse.

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REFERENCES AND FOOTNOTES

[1] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).

[2] F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

[3] R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D16, 1791 (1977).

[4] G. t'Hooft, Phys. Rev. D14, 3432 (1976); R. Jackiw and C. Rebbi, Phys. Rev. Lett. 37, 172 (1976).

[5] J. Ellis and M.K. Gaillard, DAMTP Preprint 78/6.

[6] In particular, a smaller π^o-h mixing would lower all the rates in these estimates.

[7] T. Goldman and C.M. Hoffman, Phys. Rev. Lett. 40, 220 (1978).

[8] W.A. Bardeen, S.-H.H. Tye and J.A.M. Vermaseren, Fermilab Pub-78/20-THY.

[9] The decay rate remains finite. For orthopositronium decay from the ground state (1^3S_1) into γh, we find

$$\tau_{ortho} = \frac{24\pi}{\alpha^4 g^2 m_e (1-m_h^2/4m_e^2)} \approx 8s \quad .$$

Parapositronium ($^1S_0$) decay into γh is forbidden.

[10] See, e.g., V.N. Tsytovich, Zh. Experim. i Teoret. Fiz. 40, 1775 (1961) [transl.: Soviet Phys.-JETP 13, 1249 (1961)].

[11] ν_μ and ν_τ are created by weak neutral currents only, for which we have assumed e-μ-τ universality and used the standard Weinberg-Salam model with $\sin^2\theta_W = 0.3$.

[12] Unless, of course, the Higglet has a very long lifetime. One may then put limits on the mass and lifetime of the Higglet, as has been done for new neutral leptons. See B. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977); D.A. Dicus, E.N. Kolb and V. Teplitz, Phys. Rev. Lett. 39, 168 (1977).

[13] S. Colgate and R. White originally suggested (Ap. J. 143, 626 (1966)) that a supernova explosion is triggered when neutrinos from the imploding core deposit their energy in the envelope. Of course the difficulty with this theory is that neutrinos interact very little in the envelope.

FIGURE CAPTIONS

Fig. 1 Feynman diagrams for Higglet production through (a) annihilation; (b) photoproduction and (c) plasma decay. In each case there is an additional Feynman diagram obtained by interchanging the photon and Higglet lines.

Fig. 2 Total cross section for $e^+e^- \rightarrow \gamma h$ and $\gamma e \rightarrow he$. [Eqs. (3) and (5) in the text], for the case $m_h = 50$ KeV/c^2.

Fig. 3 Higglet production rates per unit volume as a function of temperature for two values of the electron chemical potential μ_e, assuming $m_h = 100$ KeV/c^2. The dashed lines are the ν-$\bar{\nu}$ pair production rates per unit volume summed over ν_e, ν_μ and ν_τ. The Higglet rates are given in units of 10^{36} interactions/cm^3-s, and the ν-$\bar{\nu}$ rates in units of 10^{32} interactions/cm^3-s.

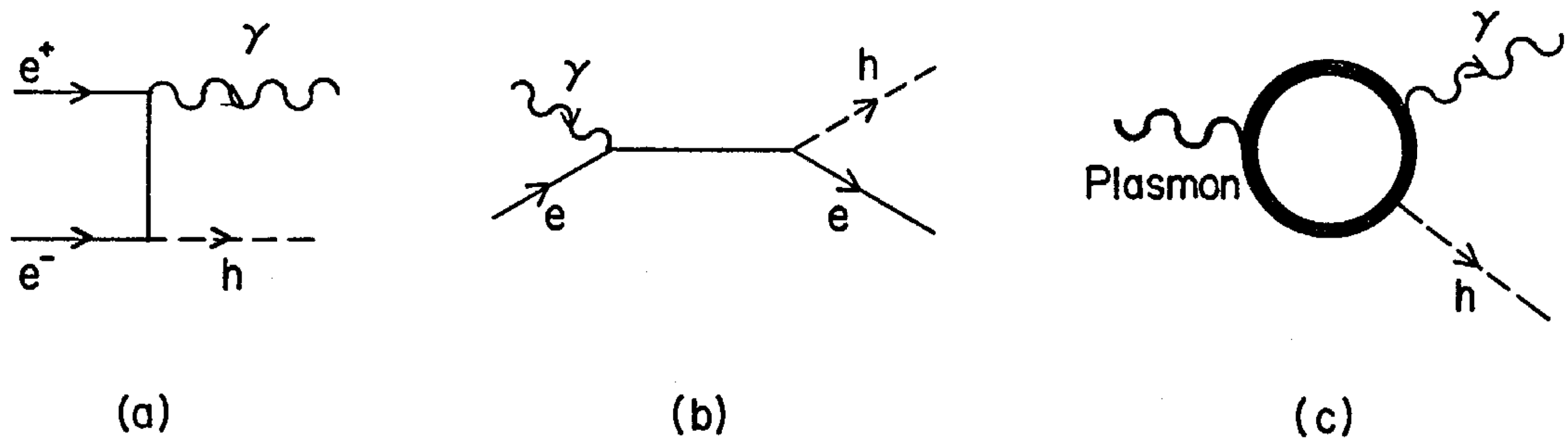
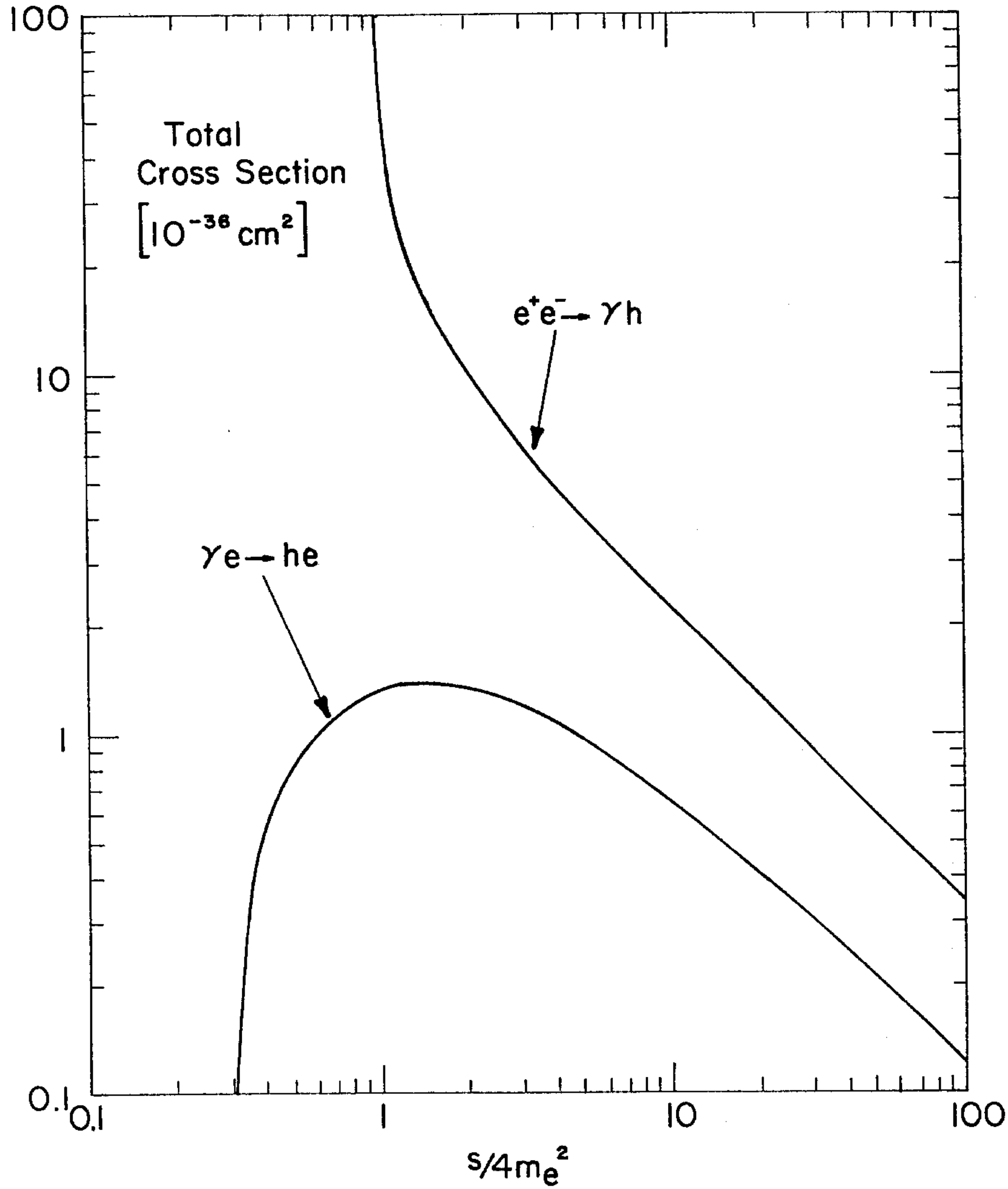
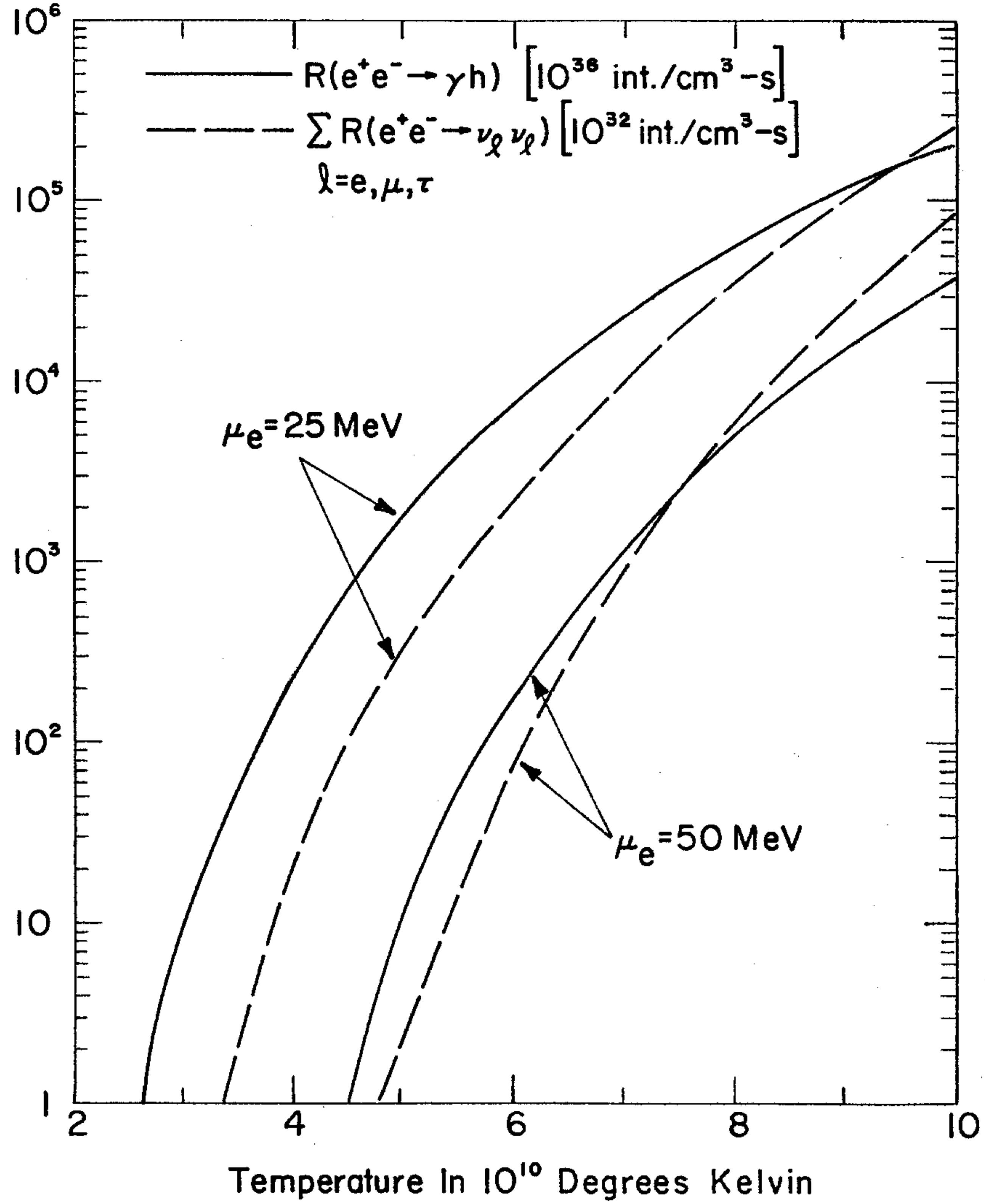


Fig. 1



100
10
1
0.1
Total
Cross Section
[10^-36 cm^2]
e⁺e⁻→ γh
γe → he
0.1
1
10
100
s/4m_e^2

Fig. 2



R(e⁺e⁻ → γh) [10³⁶ int./cm³-s]
∑ R(e⁺e⁻ → ν_ℓ ν_ℓ) [10³² int./cm³-s]
ℓ=e, μ, τ
μ_e = 25 MeV
μ_e = 50 MeV
10⁶
10⁵
10⁴
10³
10²
10
1
2
4
6
8
10
Temperature In 10¹⁰ Degrees Kelvin

Fig. 3