BREAKDOWN OF HELIUM NUCLEI IN MATTER PROCESSED NEAR BLACK HOLES

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ABSTRACT

The rate of breakup of helium nuclei by particle-induced reactions is computed. It is shown that the rate is determined by the endothermic reaction $p + {}^4He \rightarrow {}^3He + d$, becoming effective at $kT \gtrsim$ few MeV. It is suggested that matter having been processed to these temperatures will be depleted in helium and in the elements C, N, O, and Ne.

1. Introduction. In recent years considerable interest has developed in relativistic plasmas in which the electron gas is highly relativistic ($\Theta = kT/mc^2 \sim 10$). At these temperatures the ions would be non-relativistic but capable of undergoing endothermic reactions. In a recent paper [1] devoted to nuclear-force effects in p-p scattering, it was suggested that helium nuclei will break down in the following series of endothermic reactions:

$$p + {}^4He + 18.353 \text{ MeV} \rightarrow {}^3He + d \quad (1)$$

$$p + {}^3He + 5.493 \text{ MeV} \rightarrow d + p + p \quad (2)$$

$$p + d + 2.225 \text{ MeV} \rightarrow p + p + n \quad (3)$$

Because of its significantly larger threshold, the reaction (1) would be the slowest and therefore determine the rate of the overall helium-destruction process. Once the helium is broken down to hydrogen, any subsequent buildup would be very slow because of the small cross section for the fundamental p-p reaction $p + p \rightarrow d + e^+ + \nu_e$. The plasma would then remain essentially pure hydrogen. Other elements would also be broken down (see [1]), such as the abundant medium-weight C, N, O, Ne, although large Coulomb barriers are involved, since the threshold energies for the breakup reactions are much larger than in reaction (1).

The most elementary estimate of the characteristic breakdown temperature is obtained [1] by setting $kT \sim 0.1E_b$, where E_b is the binding energy difference (18,353 MeV) in reaction (1). The factor 0.1 arises since the equation for the breakdown temperature will be of the form, characteristic of ionization and dissociation phenomena,

$$e^{E_b/kT} \sim N = \text{large number} \quad . \quad (4)$$

The logarithm of any large number is ~ 10, and this yields for the breakdown temperature:

$$\Theta_b(\text{He}) \sim 4 \quad . \quad (5)$$

2. Calculation of Breakup Reaction. The calculation of the character-

istic breakdown temperature is really a non-equilibrium problem requiring a knowledge of the density (n_p) of the plasma and the available time (τ). If $r = dN/dVdt$ is the number of reaction (1) per unit volume per unit time, the breakdown temperature will be computed from

$$r\tau = n_p \ . \tag{6}$$

The rate r will be proportional to $n_p^{\ 2}$ and an integral over the reaction cross section:

$$r = \frac{1}{2} n_p^{\ 2} < v_r > \ , \tag{7}$$

where v_r is the relative velocity of the reacting protons.

The problem is in the correct use of the reaction cross section σ and in the extrapolation of its experimental values to low energies. For in this case of a reaction with a threshold energy and reactants with a Maxwellian velocity distribution, the main contribution to $<\sigma v_r>$ will come from c.m. energies just above threshold. However, then the Coulomb effects in the cross section will be very important, especially for the outgoing particles in the reaction. To include these effects the experimental cross section [2] has been fit to a form

$$\sigma = \sigma_{nuc}\ C^2 C'^2 \ , \tag{8}$$

where σ_{nuc} is a "nuclear part" and C^2 and C'^2 are (incoming and outgoing) Coulomb factors of the form [3]

$$C^2 = 2\pi\eta/(e^{2\pi\eta}-1) \tag{9}$$

for the incoming and outgoing particles. Here $\eta = z_1 z_2 (Ry_\mu/E)^{1/2}$, in terms of the charges $z_1 e$ and $z_2 e$ of the particles involved and $Ry_\mu = (\mu/m)Ry$ is the Rydberg energy corresponding to the reduced mass of the pair of nuclei. In terms of the c.m. energy (before reacting) and the threshold energy E_t for reaction (1), σ_{nuc} is found to have the form

$$\sigma_{nuc} = \sigma_{nuc-t}\ [1 - a_s(E-E_t)/E_t] \tag{10}$$

with σ_{nuc-t} = 93mb and $a_s = 0.148$.

Due primarily to the Coulomb factor C'^2 for the outgoing particles, the integrand in $<\sigma v_r>$ is found to have a "Gamow peak" where most of the contribution is centered. An asymptotic evaluation of the integral yields the following set of breakdown temperatures for given values of τn_p:

Θ_b(He)	2	3	4	5	6	7	8
τn_p(yr cm^{-3})	$1.4\text{x}10^{15}$	$3.8\text{x}10^{12}$	$2.1\text{x}10^{11}$	$3.8\text{x}10^{10}$	$1.2\text{x}10^{10}$	$5.4\text{x}10^{9}$	$3.0\text{x}10^{9}$

That is, the original estimate [1] $\Theta_b(\text{He}) \sim 4$ is reasonable, although the result does depend logarithmically on τn_p.

Although no details were given of the method of calculation, Aharonian and Sunyaev [4] have also computed the rate of reaction (1) in the high-temperature range. Their lowest T corresponds to the highest value in the above table and the results agree. However the domain

$\theta < 5$ is probably most relevant, since it is especially important to know when the process begins to be effective as the temperature rises. Further details of the calculations described in the present work may be found in a separate paper [5]. For example, competing reactions have been investigated, such as

$$\begin{aligned} p + {}^4He + 20.578\ \text{MeV} &\rightarrow {}^3He + p + n \\ p + {}^4He + 19.814\ \text{MeV} &\rightarrow {}^3H + p + p \end{aligned} \qquad (11)$$

These are found to contribute only about 1% as much as reaction (1), due essentially to the smaller cross sections for the reactions (11) at low energies (just above threshold); this is a phase space effect.

3. Discussion. In a strong gravitational potential, say, $\Phi \sim 0.1\ c^2$, it can be expected that a temperature $kT \sim 0.1\ Mc^2 \sim 100$ MeV can be attained (M = nucleon mass). This potential (and temperatures) could occur in regions around black holes, for example, and is well beyond that necessary to break up He and other nuclei. Matter that has attained this temperature can then be expected to be pure hydrogen. However, it might not be observed until after it has cooled. We would then see a recombination-cascade spectrum with only hydrogen lines after cooling to $\sim 10^5$K. While at $\sim 10^7$K there would be a pure bremsstrahlung x-ray spectrum without x-ray lines from excitations of one- and two-electron ions from the K-shell.

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References

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