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Explosive alpha capturing reactions at high temperature conditions in astrophysics

Aditi Bezbaruah Bhattcharyya

Department of Physics, Jorhat Engineering College, Horhat 785 010, India

Kalpana Duorah, H.L. Duorah

Department of Physics, Gauhati University, Gauhati 781 014, India

Abstract. It has been recognized that C^{12} (α, γ) O^{16} and O^{16} (α, γ) Ne^{20} may proceed explosively at some stellar situation; more particularly at the outer layers of pre-supernova stage of stellar evolution. The effect of temperature on the mass of nuclei involved in these reactions are studied. Corrections for finite number size and nuclear surface energy are considered. There is a considerable change in the mass along with the temperature in the region considered. With these new mass, Q values for the reactions are calculated. With these new values, it is expected that reaction may proceed through some new levels. Reaction rate for capturing reactions are modified accordingly.

Key words : pre–supernova; explosive nucleosynthesis

1. Introduction

Alpha capturing reactions may occur with rates comparable to a dynamical free fall time i.e. of the order of seconds under some extreme conditions of temperature and density. Such situations occur generally in presupernova stages of star, where shock waves are moving through the convective layers in short duration.

The C^{12} (α, γ) O^{16} reaction is considered because its rate sensitivity influences both the predicted abundance distribution of the elements (from carbon to iron) and the final evolutionary state of a massive star (Flower 1984). At low temperature (T-10^{8}°K) the main contribution to the reaction comes from the tail of a 7.12 MeV excite state of O^{16}. This state has a reduced alpha width $\theta_{\alpha}^{2} = 0.053$, (Flower 1975) so the rate does not seem to be faster. But at higher temperature prevalent at the pre-supernova stage some higher energy level with right spin and parity might contribute to the rate. At the high temperature attained to time of bounce a large numbers of nuclear level densities become important (Datta & Ray 1989). The excited states of O^{16} shows that the levels are at 7.117 (1^-) Mev, 872 (2^-) Mev, 9.632 (1^-) Mev .847 (2^+) Mev. The resonance of importance in the stellar situation at temperature $T^9 = (T\backslash 10^9)$ are those which lie near the effective thermal energy $E_0 = .922\ T_9^{2\backslash 3}$, $\delta E_0 = .6150\ T_9^{5\backslash 6}$ Mev. Hence as the temperature rises the reaction will proceed through the higher excited state at 9.641 (1^-) Mev level. Koonin *et al.* (74) showed that the cross section factors S(E) for $C^{12} + \alpha = O^{16} + \gamma$, including the effect of the bound states gives better agreement with the experimental data. While inspecting the excited state of O^{16}, it is seen the structure of S(E) is dominated by a broad resonance at 2.470 kev above the threshold which includes the 9.632 (1^-) and 9.847 (2^+) states. Davidson *et al.* (1994) have determined a temperature dependent mass formula for application in the region where high energies are experienced. In this paper the effect of temperature on the mass of nuclei hence on the Q value of the nuclear reactions are studied. With this change of Q values a change in the abundance pattern of the nuclei is envisaged.

2. Temperature dependent mass formula

The semi emperical mass formula provides a simple parameterization of binding energy for all known nuclei. The mass M of a neutral atom whose nucleus contains Z protons and N neutrons is

$$M = M_n N + M_p Z - \alpha A + \beta A^{2/3} + (\gamma - \eta / A^{1/3})\,(T_\zeta^2 + 2/T_\zeta) + .8076\ z^2 / A^{1/3}\,(1 - 0.7636 / z^{2/3} - 2.29 / A^{2/3}) \quad (1)$$

where, $\alpha = 16.11$ Mev $\qquad \gamma = 20.65$ Mev

$\beta = 20.21$ Mev $\qquad \eta = 48.00$ MeV (Davidson 94)

As we concentrate our study on temperature corrections for finite nuclear surface energy only assuming that the temperature dependent binding energy has a similar form as the usual semi empirical mass formula.

$$M = M_n N + M_p Z - \alpha\,(T) A + \beta\,(T) A^{2/3} + (\gamma - \eta / A^{2/3})\,(T_\zeta^2 + 2/T_\zeta) + .8076\ z^2 / A^{1/3}\,(1 - 0.7636 / z^{2/3} - 2.29 / A^{2/3}) \quad (2)$$

where, α (T) and β (T) are temperature dependent volume energy and surface energy co-efficients.

We have taken α (T) form Davidson *et al.*

$$\alpha\,(T) = -16 + 0.15\ T^2$$

and calculated β (T) as polynomial solution from the available experimental graphs (Davidson 94)

$$\beta\,(T) = a + bT + CT^2 + dT^3 \quad (3)$$

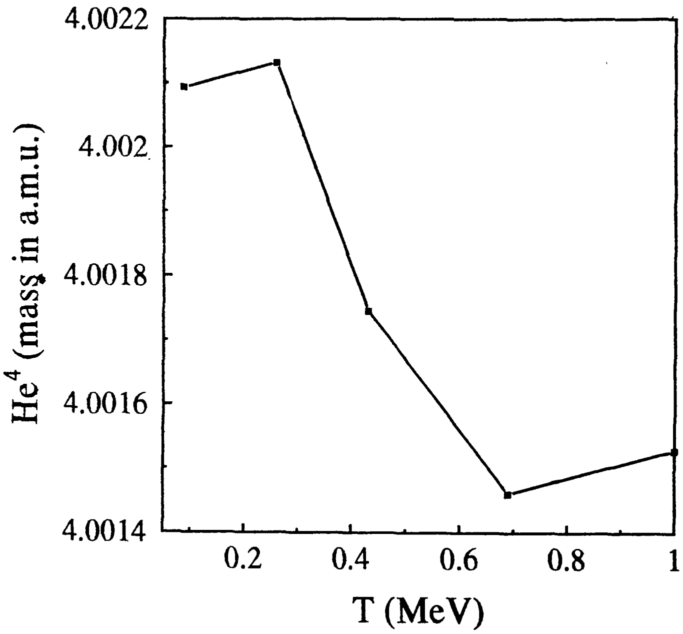

Figure 1. Mass of He^4 nuclei at different temp.

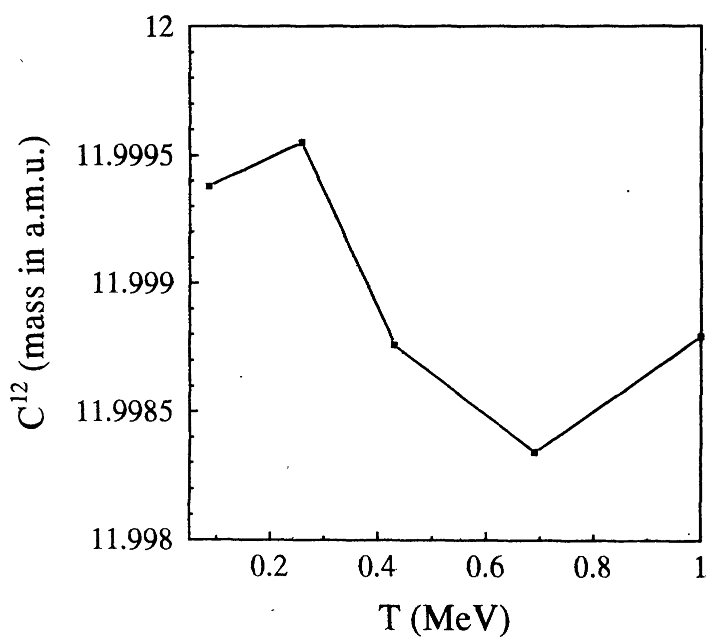

Figure 2. Mass of C^{12} nuclei at different temp.

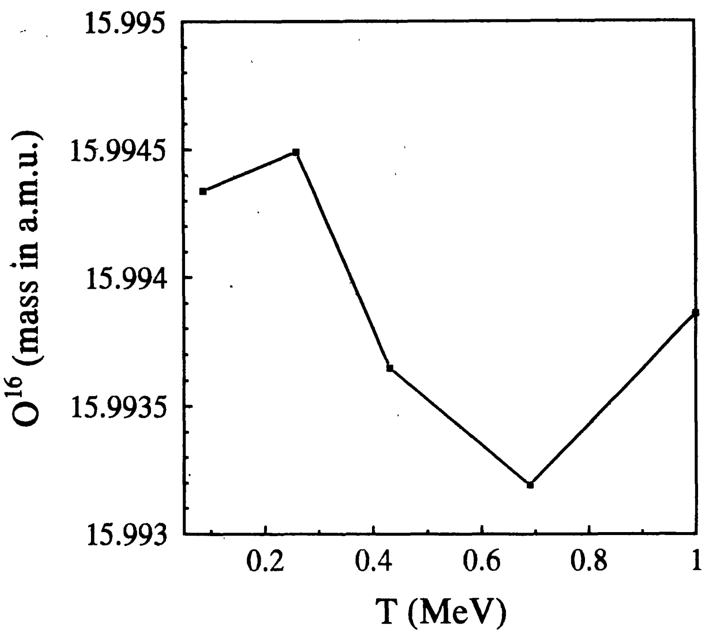

Figure 3. Mass of O^{16} nuclei at different temp.

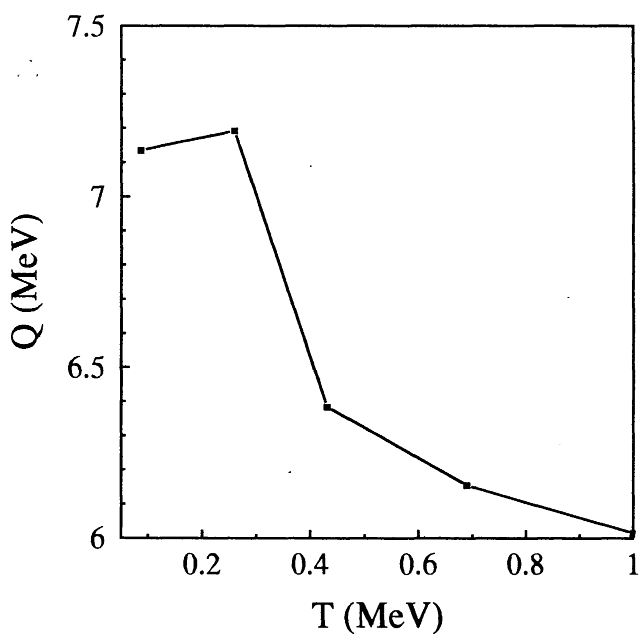

Figure 4. Values of Q at different temp.

a = 20.2   b = −1.617   c = 1.0   d = .183

Values of α (T) and β (T) are shown in table 1. We have considered the temperature up to 1 Mev only.

Table 1.

T^0K Temp.	E (Mev) Independent	α (T) Mev 16.11	β (T) Mev 20.21
10^9	.08625	15.99888414	19.845443454
3×10^9	.25875	15.9899574	19.84538257
5×10^9	.43125	15.97210352	19.67396827
8×10^9	.69	15.928595	19.50025281
11.59×10^9	1	15.85	19.4

By using these temperature dependent co-efficients the masses of the nuclei are calculated, and results are shown in table 2.

Table 2.

T (Mev)	He^4 (amu)	C^{12} (amu)	O^{16} (amu)	Q (Mev)
.086	4.002603	12	15.994915	7.157528
.086	4.002093672	11.99937973	15.9943381	7.135302
.25875	4.002131886	11.99955079	15.99449127	7.1914108
.43125	4.001744644	11.99875957	15.99364739	6.3837031
.6	4.001461442	11.99834248	15.99319215	6.155559732
1	4.001527735	11.99879097	15.99385895	6.014031905

From the above table we have seen that the masses of the nuclei are changes with temperature. Therefore Q values of the equation will also change with temperature. We have drawn M – T and Q – T curves which show the variation of mass and Q with temperature. With the change of Q, the nuclear reactions may proceed through some new levels. Considering the change in Q values due to temperature, reaction rates are modified accordingly. Therefore, our conclusion is that this change in reaction rate will bring substantial change in nuclear abundances.

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