PROCEEDINGS OF SCIENCE

Nuclear reactions in very hot astrophysical plasmas with temperatures $T > 10^{10}$ K

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We use the public available TALYS code to study the spectral and temporal evolution of nuclear reactions in low-density astrophysical plasmas with ion temperatures $T \geq 10^{10}$ K. Such studies are of great interest in the context of scientific programs of future low-energy cosmic gamma-ray spectrometry. The reaction rates logarithm have been fitted as a polynomial function of temperature with seven free parameters. This makes this network convenient for calculations of reactions, especially in the case of time-dependent plasma temperature. We study the chemical abundance and gamma-ray lines emissivity evolution, and present some preliminary results for light elements such are D, T, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}Be.

25th Texas Symposium on Relativistic Astrophysics - TEXAS 2010
December 06-10, 2010
Heidelberg, Germany

PoS(Texas 2010)274

1. Introduction

Low-density optically thin, hot plasmas with ion temperature exceeding 1 MeV can be formed near compact relativistic objects, such as accretion flows close to black holes [1] and in strong shock waves related, for example, to supernova explosions [2]. The most straightforward approach to studying the dynamics of formation and evolution of such plasmas is the detection of prompt γ-ray lines which are unambiguous signatures of specific nuclei. Collisions in thermal plasmas with temperatures exceeding 1 MeV are characterized not only by excitation reactions with emission of gamma-ray lines, but also by the destruction of nuclei. In such plasmas, the destruction of nuclei proceeds on timescales shorter than excitation times. Thus, only prompt de-excitation lines related to specific nuclei are expected to contribute to the plasma radiation [4]. The presence of a given prompt gamma-ray line is related to the existence of a given nucleus, which is itself governed by the destruction processes. This suggests that there should exist a strong relation between the gamma-ray line spectrum and nuclear destruction processes.

The break-up processes are sensitive to the plasma temperature and density. Therefore, the detection of gamma-ray lines and their spectral profile evolution may reveal unique information about the chemical composition and physical parameters of the plasma, such as temperature and density at any given time.

The first attempts to assess the importance of nuclear processes in hot, thin astrophysical plasmas were made in [3, 4]. There, the contribution of the expected strong gamma-ray lines to the luminosity of spherically symmetric accretion flows and accretion disks, is estimated. They have found that even in the most favorable conditions, temperatures and composition, the luminosity of this line would be low, such that it was impossible to be detected with γ-ray instruments of that time. In [3, 4], is also suggested a mechanism to produce light elements in a astrophysical way. In particular they discuss a mechanism for deuterium production in such plasmas and nearby environment. In these early works, however, only a limited number of reactions could be taken into account, mainly due to the lack of data on nuclear cross sections and the increased computational complexity of calculations as more nuclei are considered.

Most of these difficulties have nowadays been overcome. The introduction of on-line nuclear databases [5, 6] provides easy access to experimental and theoretical data on nuclear cross sections. There also exist publicly available computer codes that allow the calculation of nuclear cross sections and other quantities of interest. These make use of several theoretical models.

In this work we calculate the temporal evolution of the composition and the gamma-ray line luminosity of a hot plasma with ion temperature $T_{\mathrm{i}} \geq 1$ MeV due to nuclear reactions. We show the amount of light elements that can be formed in such plasmas when the temperature and densisty remain constant. Although we presently concentrate on the radiative output, the study of nuclear reactions in hot plasmas may have other relevant applications, such as calculating the production of deuterium nuclei and its associated γ-ray line in an astrophysical way. The production of neutrons is also of considerable interest, since these particles can escape from the source and interact with nearby targets.

2. Method and Calculations

The most important ingredient for calculating chemical and γ-ray lines luminosity evolution are the reaction rates. We are going to take for initial composition the cosmic composition [8]. Moreover as we have already discussed, all heavy nuclei are quickly destroyed, therefore in a short time scale < 1 sec for $T > 1$MeV, we are left over with light species only. This property allow us to neglect all heavy nuclear interactions. We have considered reactions with neutrons, protons and alpha particles as projectiles. This is a good approximation for plasmas with a standard cosmic composition [8]. Furthermore, we assumed that all nuclei are instantaneously in thermal equilibrium at the same temperature T, and that they are all interacting in their ground state. To calculate the composition evolution we basically have to solve the Boltzmann's equation for every nuclear species in the plasma. The basic ingredient in these equations is the Maxwellian average $<\sigma v>$, where σ is the cross section and v the relative velocity between projectile and target. We call $<\sigma v>$ simply as the rate. We have built a closed reaction network where every reaction produce nuclei which are in the network. Our network includes reactions of the nuclei with neutrons, protons and alphas. The network includes nuclear species from n, ^{1}H up to ^{70}Zn. We calculate the cross sections from ^{6}Li to ^{70}Zn we have calculated by using TALYS, whereas the cross sections for ^{1}H, D, T, ^{3}He and ^{4}He interactions with protons, neutrons and alphas we took from ENDF-VII.1 evaluations and for the reactions where evaluations are missing we have taken the experimental data to reconstruct the cross sections as a function of projectile LAB energy. Below we are showing some cross sections examples and their respecting rates.

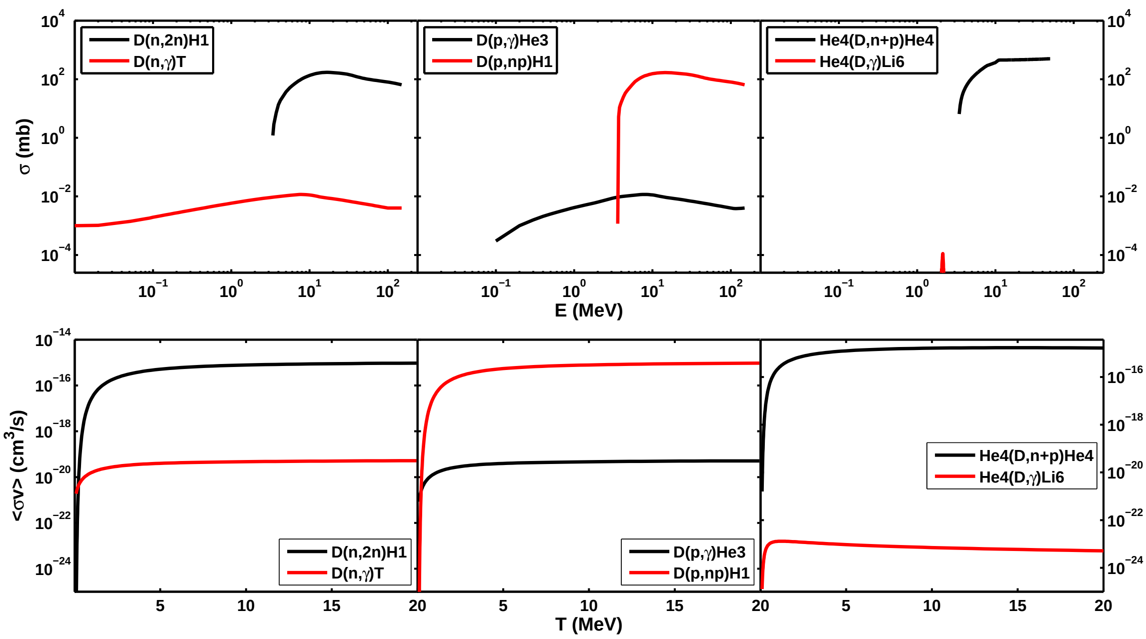

Figure 1: The cross sections of Deuterium interactions taken from ENDF-VII.1 and their corresponding rates $<\sigma v>$.

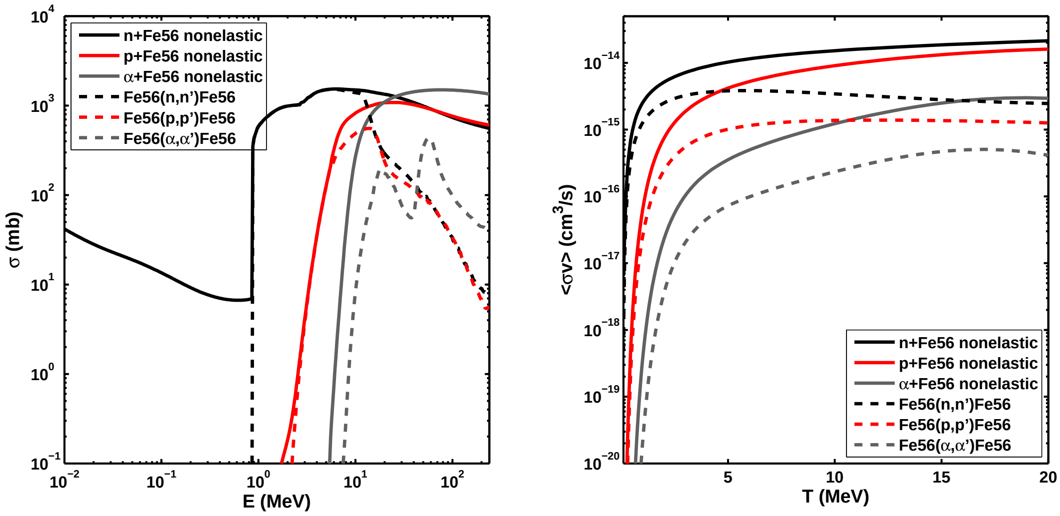

Figure 2: The total nonelastic and inelastic cross sections of ^{56}Fe, computed with TALYS, and their corresponding rates $<\sigma v>$.

3. Discussion

We validated our network by calculating the mass abundance evolution of all the nuclei in a simple case. The initial mass fractions are $X_p = 70\%$, and $X_{^{56}\mathrm{Fe}} = 30\%$, and the total nucleon number density is $\rho = 10^{18}\,\mathrm{cm}^{-3}$. We solved the network for two different temperatures, $T = 1$ MeV and $T = 10$ MeV.

Figure 3 shows the temporal evolution of the mass fraction abundances and the number of photons of a certain type per unit time and volume. The value of the temperature has a strong impact on the characteristic timescales. The rates of almost all reactions increase with temperature, and correspondingly the abundances of nuclei and the gamma-ray emission evolve much faster. Note from Fig. 3 that some intermediate elements (result of break-up processes) become more abundant in certain periods of the evolution. At higher temperatures more interaction channels are opened, which leads to more γ-ray lines due to the de-excitation of nuclei. For temperatures $T \geq 1$ MeV the plasma quite quickly destroys all heavier nuclei, and the final state contains just protons and neutrons and some small traces of Deuterium and ^{4}He, result of break-up processes and weak fusion reactions which take place on larger time scales. At this stage the gamma-ray emission almost disappears.

Figure 4 shows the temporal evolution of the mass fraction abundances of stable light elements for mass numbers up to $A = 11$. We see there, that the light elements such as Li, Be and B are practically negligible. Whereas the Hydrogen and Helium isotopes are much more abundant result of Deuterium synthesis of neutron capture by Hydrogen. This reactions will remain in equilibrium until neutrons and protons remain in equilibrium.

By this simple case, we can draw some general inferences of $T > 1$MeV plasmas. These plasmas tend to destroy quickly all heavier nuclei. In a first approximation we may conclude that for time scales $\tau < 1$ secondwe plasma ends up with formation of a proton-neutron plasma. Result of proton-neutron plasma formation, is that all gamma-ray lines emission disappear. For time scale

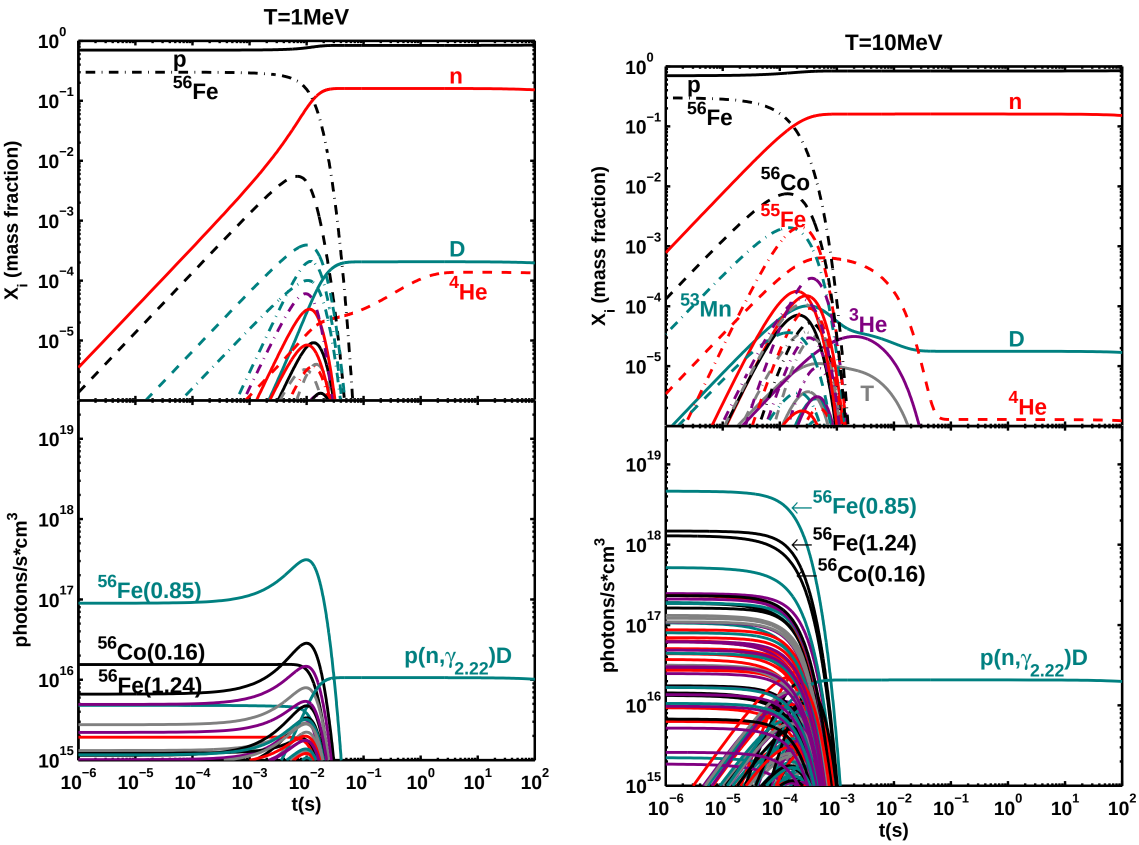

Figure 3: Temporal evolution of the mass fraction abundance X_i and the plasma in gamma-ray lines emission per unit time and volume, calculated for temperatures $T = 1$ MeV and $T = 10$ MeV and initial abundances $X_p = 70\%$, and $X_{^{56}\mathrm{Fe}} = 30\%$.

$\tau > 1$ second, neutron capture by protons through reaction ^{1}H(n,γ)D can produce Deuterium (D) and emission of 2.22MeV γ-ray which from energetics should be broader line as is calculated in [3]. The future of this plasmas is to become "absolute" proton plasma due to neutrons decay, unless neutrons can escape the plasma due to the so called neutron evaporation calculated in [3].

Future work will consist of solving the network for realistic conditions concerning the temporal and spatial dependence of the density and temperature realized in specific astrophysical environments, e.g. accretion flows in the vicinity of black holes and in strong shock waves related to supernova explosions.

References

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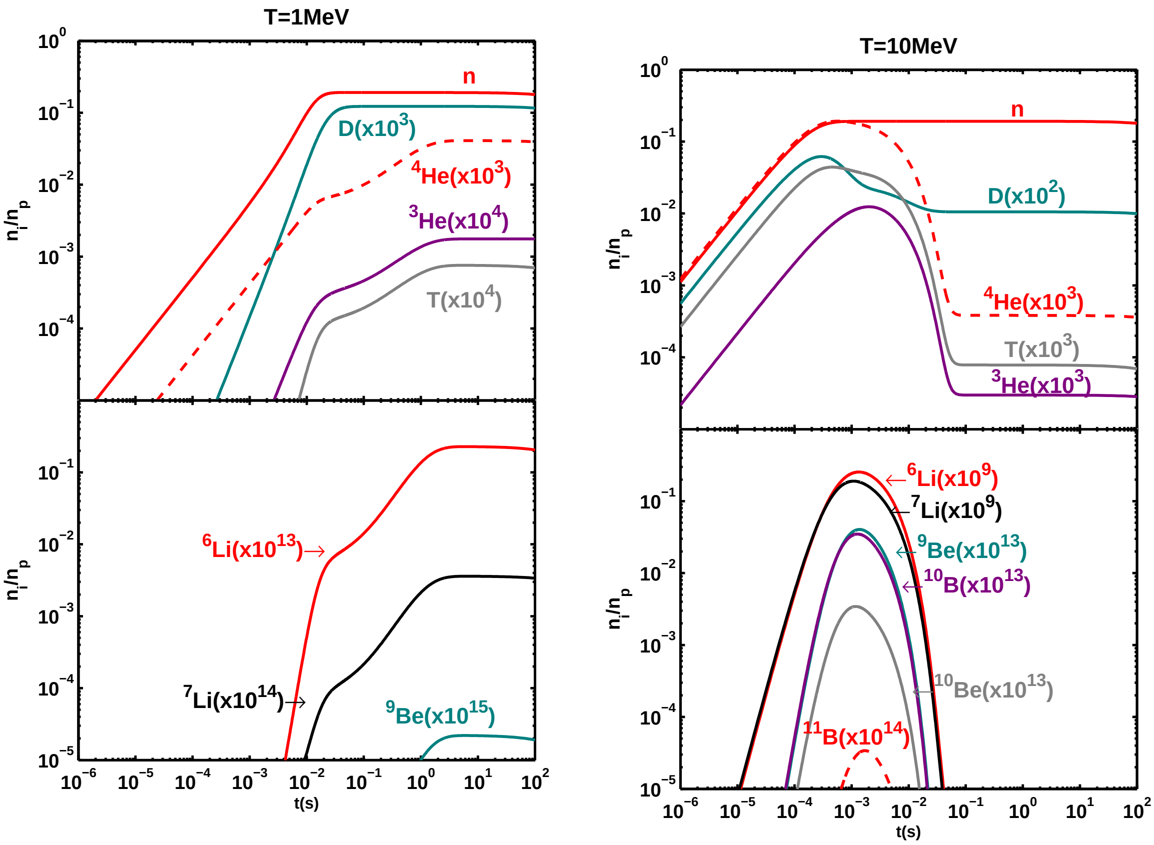

Figure 4: Temporal evolution of the mass fraction abundance for light elements upper plots for mass number nuclei $A = 1-4$ and lower plots for $A = 6-11$, calculated for temperatures $T = 1$ MeV and $T = 10$ MeV and initial abundances $X_p = 70\%$, and $X_{^{56}\mathrm{Fe}} = 30\%$. Inside brackets is the coefficient which multiply the X_i in order to bring at a comparable scale.

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[6] **NNDC-BNL**, National Nuclear Data Center, Brookhaven National Laboratory, *http://www.nndc.bnl.gov/*

[7] **TALYS code**, Arjan Koning, Stephane Hilaire, Marieke Duijvestijn, *http://www.talys.eu*

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