Ionization Potential Depression and its effect on Saha Ionization Equation in Stellar Environment

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Introduction

The ionization potential is the energy required to free an atomic bound electron to continuum state. The ionization potential of an atom embedded in matter in thermodynamic equilibrium gets reduced. Then the energy of zero-kinetic-energy electron becomes non-zero in the medium [1, 2]. One can think of it as the lowering of the continuum of an atom or ion when surrounding is non-empty. This phenomenon is known as Ionization Potential Depression (IPD).

The ionization potential is an important ingredient while using Saha Ionization Equation (SIE) [3]. SIE deals with ionization potential of every charge state while providing a clear view about the fractional percentage of different ionized states of a particular species as a function of temperature and free electron number density. For this reason, modification of ionization potential is essential when solving Saha Ionization Equation.

Moreover, for a precise view of various nuclear properties, such as β^- decay processes in stellar environment, the accurate idea of fractional percentages of various ions of an atomic species is necessary. For this purpose, an exact solution of SIE is very essential.

Motivation

In this paper, we have calculated the IPD based on three different kinds of models, viz.; i) depression of the continuum and effective ionization potential (Based on the framework of "Debye-Hückel model") [2]; ii) the zero-temperature ionized gas model [4]; iii) Modified model of Takahashi and Yokoi (TY) [5]. We have studied the variation of IPD with temperature, electron number density, atomic number, and charge states, all the physical quantities ranging within a stellar environment, preferably, an environment which is found in AGB (Asymptotic Giant Branch) stars.

After getting the IPD, we have inserted this modified ionization potentials (i.e., ionization potential -IPD) of corresponding species in Saha Ionization Equation. This introduced changes in the results of SIE i.e., we observed deviations in the values of fractional percentages of various ions for a species from their previous values that are calculated without inclusion of IPD. In this work, we have chosen some s-process elements like Nickel, Silver and Cesium for these calculations.

Results and Discussions

The first model we used here to calculate the IPD, was developed by Debye and Hückel by introducing the idea of ion spheres (often called the Debye Sphere). The second model also

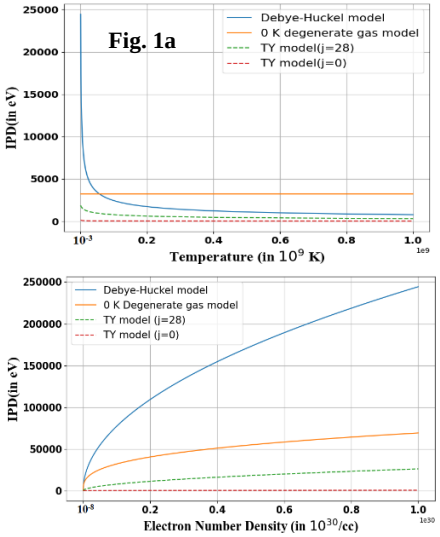


Figure 1 Comparison of the variation of IPD in different models a) with Temperature (electron number density = 10^{26}/cc); b) with Electron Number Density (Temperature = 10^8 K)

consists of the idea of ion sphere but with the assumption of relatively low temperature and high density and degenerate ionized gas medium. Finally, one of the comparatively recent models to calculate the IPD is due to Takahashi and Yokoi. It was developed based on the concept of Thomas-Fermi model and Stewart-Pyatt Plasma Field model. These three models give different values of IPD but interestingly their variations with temperature and number density have the same nature. IPD from TY model is independent of atomic number (Z) but depends on the charge state (j) of the atom, and is applicable in the range of temperature 10^6 – 10^9 K and free electron number density 10^{22} – 10^{30}/cc. Also, this model is fitted for the environment where surrounding medium consists of 75% Hydrogen and 25% Helium. This kind of environment is mostly found in s-process sites like stellar interior of AGB stars. In fig.1 the comparison of variation of IPD with temperature for different models has been shown.

The blue curve corresponds to the first model and orange curve in graph is for the second model (in which IPD is independent of temperature) for a Nickel (Z = 28) atom. The dotted curves correspond to TY model (red one for the neutral charge state and green one for charge state X^{28+}).

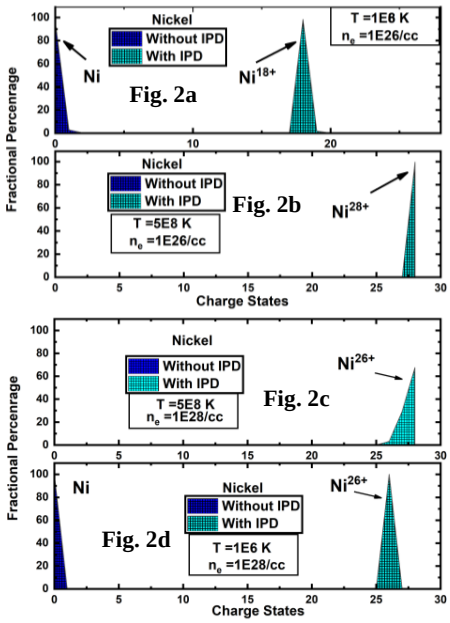
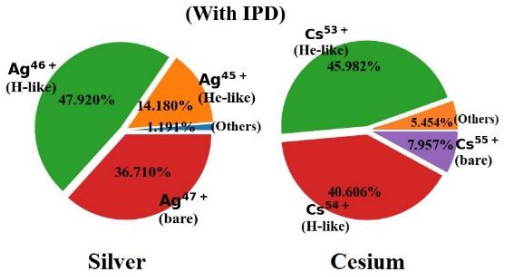


Figure 2 Effect of IPD on the result of Saha Ionization Eqn. at different temperatures and free electron densities.

Then, we have applied the IPD in Saha Ionization Equation. The effect of modifying the ionization potential while solving Saha Ionization equation is shown in the fig.2 for the case of Nickel. It has been observed that at comparatively low temperature IPD has a huge impact on the results of SIE, while for higher temperature IPD has no significant impact on SIE. Also, as the temperature reaches ~10^8 K with free electron number density 10^{26}-10^{28}/cc the probability of getting bare atom increases.

The interesting fact is that even for comparatively higher Z elements, at a temperature ~10^8 K there will be a notable fraction of bare



atoms in stellar environment. In Fig. 3 the fraction of different charge states for Ag and Cs have been presented.

To summarize, we have compared three different models for IPD in stellar environments. The modified ionization potential is used in solving the Saha ionization equation. At relatively lower temperatures the inclusion of IPD has a noticeable impact on the results.

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References

[1] J.C. Stewart and K.D. Pyatt, Jr., Astrophys. J. **144** (1966) 1203

[2] D. D. Clayton, Principles of Stellar Evolution and Nucleosynthesis, The University of Chicago Press, Chicago and London, 1983.

[3] M. N. Saha, 1921Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. **99** (697): 135.

[4] E. E. Salpeter; Energy and Pressure of a Zero-Temperature Plasma, Astrophys. J. **134** (1961) 669.

[5] K. Takahashi and K. Yokoi; Nuclear Physics **A404** (1983) 578.