Quantum Statistical Corrections to Astrophysical Photodisintegration Rates

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Tabulated rates for astrophysical photodisintegration reactions make use of Boltzmann statistics for the photons involved as well as the interacting nuclei. In this work[1] we have derived analytic corrections for the Planck-spectrum quantum statistics of the photon energy distribution. These corrections can be deduced directly from the detailed-balance condition without the assumption of equilibrium as long as the photons are represented by a Planck spectrum. Moreover we have shown that these corrections affect not only the photodisintegration rates but also modify the conditions of nuclear statistical equilibrium as represented in the Saha equation. We deduced new analytic corrections to the classical Maxwell- Boltzmann statistics which can easily be added to the reverse reaction rates of existing reaction network tabulations.

The key expressions in this work are the determination of revised thermonuclear reaction rates as,

$$\begin{aligned} \lambda_{\gamma 3} &= (1+R)[N_A\langle\sigma v(T_9)\rangle^*]_{12} && (1)\\ &\times\ 9.8685\times 10^9(\hat{\mu}T_9)^{3/2}\frac{G_1G_2}{G_3(1+\delta_{12})}e^{-11.605Q/T_9}\ , \end{aligned}$$

where T_9 is the temperature in units of 10^9 K, N_A is Avagadro's number, $[N_A\langle\sigma v(T_9)\rangle*]$ is the tabulated thermonuclear reaction rate[2] in units of $\mathrm{cm}^3\ \mathrm{mol}^{-1}\ \mathrm{s}^{-1}$, Q is in units of MeV, and $\hat{\mu}$ is the reduced mass in atomic mass units. There is also a revised Saha equation of NSE

$$\begin{aligned} \frac{X_1X_2}{X_3} &= 9.8685\times 10^9(1+R)\frac{T_9^{3/2}\hat{\mu}^{5/2}}{\rho}\\ &\times\ \frac{G_1G_2}{G_3(1+\delta_{12})}e^{-11.605Q/T_9}\ . && (2) \end{aligned}$$

The quantity R in the Egs. (1) and (2) is the new correction for the difference between Maxwell Boltzmann and Planckian statistics for the photons. We have shown [1] that this correction factor can be written

$$R=\sum_{n=2}^{\infty}\frac{1}{n^{3/2}}\frac{[N_A\langle\sigma v(T_9/n)\rangle^*]}{[N_A\langle\sigma v(T_9)\rangle^*]}e^{-11.605(n-1)Q/T_9}\ , \qquad (3)$$

The advantage of writing the expression this way is that it can be quickly deduced from existing reaction rate tables such as REACLIB[2].

The deviation of photodisintegration and NSE due to quantum statistics may impact the evolution of explosive nucleosynthesis environments for which one can encounter nuclei with small photodissociation thresholds, e.g. near the neutron or proton drip lines. To the extent that such nuclei are beta-decay waiting points, for example, the altered statistics will affect the timescale for the build up of abundances. Another possible application of the corrections deduced here is for the ionization equilibrium of atomic or molecular species with a low ionization potential in stellar atmospheres.

We have examined possible effects of these corrections on the *r*-process, the *rp*-process, explosive silicon burning, the γ-process, and big bang nucleosynthesis. We find that, in most cases one is quite justified in neglecting these corrections. The correction is largest for reactions near the drip line for an *r*-process with very high neutron density, or an *rp*-process at high-temperature[1] .

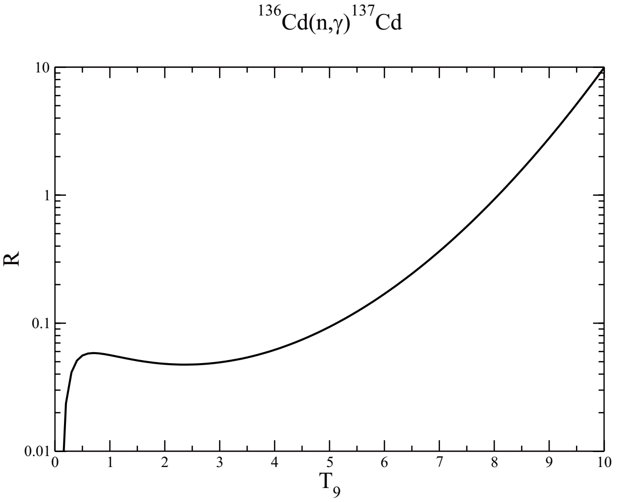

Figure 1: Correction factor R for the reverse rate of the ^{136}Cd(n, γ) ^{137}Cd reaction relevant to the *r*-process abundance peak near $A = 130$ for a high neutron-density environment. This was generated from Eq. (3) using the REACLIB compilation[2]. For typical r-process temperatures, $T_9 \sim$ 1–2, the correction is ~6%.

References

[1] Mathews, G., et al.: 2011, *ApJ*, **727**, 10.
[2] Cyburt, et al.: 2010, *ApJ*, **89**, 240; (REACLIB): http://groups.nscl.msu.edu/jina/reaclib/db/