

## M02T.2—Hydrogen Formation

### Problem

In this problem we investigate the formation of hydrogen atoms in the early universe. Although the binding energy of hydrogen is  $13.6\text{ eV}$ , the majority of protons and electrons did not become bound into atoms until the temperature of the neutral primordial plasma cooled to about  $0.3\text{ eV}$ .

In the following we make four assumptions:

1. The hydrogen atom has no bound states apart from its ground state.
2. We ignore other bound complexes that might be formed, e.g., hydrogen ions and molecules.
3. All interactions among hydrogen atoms, protons and free electrons are ignored (apart from the fundamental process of atom formation).
4. Everything is in thermal equilibrium.

There are two questions:

- a) Assume that at  $T = 0.3\text{ eV}$  half of the protons had a bound electron. From this information calculate the densities (in units of particles per cubic centimeter) of free electrons, free protons, and hydrogen atoms.
- b) At  $T = 0.3\text{ eV}$  what is the density of photons? Is it much smaller than, comparable to, or much larger than the densities obtained in part a)?