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Non-standard mechanism of the formation of hydrogen in the early Universe

Tamaz Kereselidze
Tbilisi State University, Georgia

For cosmology the formation of atomic hydrogen in the recombination epoch of evolution of the early Universe (redshift 800 < z <2000) is of special importance because that allows us to treat the thermal history of the Universe. For observations a crucial fact is that the spectrum of the cosmic microwave background (CMB) experienced a unique distortion due to the release of photons during the recombination epoch. These additional photons formed, together with the thermal spectrum, a cosmological recombination spectrum. Because the ratio of CMB photons and baryon number densities is enormous, the recombination photons constitute only a small fraction (10^{-9}-10^{-8}) of the total amount; their distorting influence on the CMB spectrum is hence small.The pioneering works of Peebles [1] and of Zel'dovich, Kurt & Syunyaev [2] revealed that any direct combination of an electron and a proton, and thereby the formation of atomic hydrogen in the ground state, was immediately followed by the ionization of an adjacent atom due to re-absorption of the newly released photon. An electron and a proton combined efficiently into the hydrogen atom only in excited state, from which a rapid cascade occurred into a state with principal quantum number n = 2 . A radiative decay from state 2 p involving one photon or from state 2s involving two photons then yielded the hydrogen atom in its ground state. The decay 2p →1s led to the appearance of photons with energy sufficient for the Lyman-α resonance excitation of atomic hydrogen already formed in the ground state. The 2p →1s decay processes were thus compensated by the excitation process. The 2s → 1s two-photon decay, which is about eight orders of magnitude slower than the 2pc 1s one-photon decay, was thus the dominant process for the formation of hydrogen in the ground state.Despite substantial progress achieved after the works of Peebles and Zel'dovich et al., there remain problems concerning the details of cosmological recombination. One problem is an impact of the nearest neighbouring proton on an electron-proton recombination. This impact was obviously significant at the pre-recombination stage of evolution of the Universe when the temperature and density of matter were higher than subsequently, and decreased when the density of protons decreased, i.e. when a redshift z decreased. The average distance between protons in the pre-recombination stage of evolution of the Universe is estimable if one assumes that, before recombination, the reaction $e+p \rightleftarrows H+\hbar\omega$ was in statistical equilibrium, i.e. the rate of radiative recombination was balanced with the rate of photoionization. In statistical equilibrium at temperature T , the number density of particles is given according to the Maxwell-Boltzmann equation. Writing this equation for the hydrogen atoms, protons and free electrons, we obtain the Saha-Boltzmann equation that relates the number densities of these particles. Making use of this equation, we can find the average distance between protons R as a function of redshift z . An estimation shows that at redshift z = 2500 the average distance between protons was $\overline{R}$ = 9.4 x 10^{-4} cm. This magnitude is comparable with a linear size of the hydrogen atom in an excited state with n = 300 . In the pre-recombination stage of evolution the combination of an electron and a proton thus occurred in the presence of the nearest neighbouring proton, which participated in the process

According to the non-standard, quasi-molecular mechanism of recombination (QMR), an electron collides with two protons situated one far from another, emits a photon and creates quasimolecule H_2^+ in a highly excited state. In an adiabatic representation the energy terms of H_2^+ are divided into repulsive and attractive according to their behaviour at large distances R between protons. The hydrogen atom and a proton hence move away from each other if H_2^+ is formed in a repulsive state, whereas these particles approach each other if H_2^+ is created in an attractive state.This effect means that the quasi-molecule H_2^+ dissociates into a hydrogen atom and a proton when itis formed in a repulsive state, and H_2^+ descends into a low-lying quasi-molecular state when it is created in an attractive state. We can thus deduce that the QMR leads to a transition of two types in the temporarily formed quasimolecule: bound-free with a formation of atomic hydrogen and a proton, and bound-bound with a subsequent formation of H_2^+ in the ground state. The presence of another proton reduces the symmetry of a field experienced by an electron involved in the recombination from spherical to axial and leads to a Stark splitting of the hydrogen energy levels. These two effects lead in turn to radiative transitions that are forbidden in the recombination of an electron with an isolated proton. The participation of the nearest neighbouring proton in the process thus opens quasi-molecular channels, and hence has an impact on the recombination history. In our recent papers [3-6], we have studied qualitatively and quantitatively the influence of the QMR on cosmological recombination. The obtained results can be summarized as follows: (i) the existence of attractive quasi-molecular terms leads to the effect that a portion of electrons involved in the recombination settles in the ground state of H_2^+ and, accordingly, does not participate in the formation of hydrogen; (ii) the probability of the formation of H_2^+ in the ground state is comparable with the probability of the creation of atomic hydrogen; (iii) the participation of a second proton in the recombination increases the binding energy of an electron and hence shifts beginning of the stage of the standard recombination towards earlier period. The QMR naturally transforms into the standard mechanism of recombination when z decreases. More details will be reported at the presentation.

Biography

T. Kereselidze graduated from Tbilisi State University, and then he was a post graduate student at Kurchatov Atomic Energy Institute in Moscow. T. Kereselidze defended his candidate thesis in the Kurchatov Atomic Energy Institute in 1977, and then the doctoral thesis at Tbilisi State University in 1993. T. Kereselidze is the author of about one hundred scientific articles, published in high level international and soviet journals. Since 2006 T. Kereselidze is professor of faculty of exact and natural sciences at Tbilisi State University and head of chair of atomic and nuclear physics.