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

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For cosmology the formation of atomic hydrogen in the recombination epoch of evolution of the early Universe (redshift $500 < z < 2000$) 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 photon 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. Despite substantial progress achieved in the study of the CMB spectrum there remain problems in our understanding of cosmological recombination.

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 $2p$ involving one photon or from state $2s$ involving two photons then yields the hydrogen atom in its ground state. The decay $2p \to 1s$ leads to the appearance of a photon with energy sufficient for the Lyman-α resonance excitation of atomic hydrogen already formed in the ground state. The $2p \to 1s$ decay processes are therefore compensated by the excitation processes. The $2s \to 1s$ two-photon decay, which is about eight orders of magnitude slower than the $2p \to 1s$ one-photon decay, is thus the dominant process for the formation of hydrogen in the ground state.

The average distance between protons in the 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 derived equation, we found the average distance between protons $\overline{R}$ as a function of redshift z.

In the pre-recombination stage of evolution of the Universe the temperature and density of matter and radiation were higher than subsequently. An estimation shows that at redshift $z = 2500$ the average distance between protons was $\overline{R} \simeq 2200\, a_0$ ($a_0 = 0.529 \times 10^{-8} cm$ is the first Bohr radius of hydrogen). This magnitude is comparable with a radius of the hydrogen atom in an excited state with $n \simeq 30$. 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 quasi-molecule H_2^+ in a highly excited state, which then dissociates into a hydrogen atom and a proton or descends into a low-lying state [3]. The QMR thus leads to a radiative transition of two types: bound-free with a formation of atomic hydrogen and a proton, and bound-bound with a subsequent

formation of H_2^+ in its ground state [4]. The influence of the nearest neighbouring proton on the recombination decreases when the density of protons decreases. This condition means that the QMR transforms into the standard mechanism – the recombination of an electron on an isolated proton when redshift z decreases. The standard mechanism of recombination is hence a limiting case of the QMR.

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 [3-5], we have studied 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 part of the 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 its 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 decreases the rate of formation of hydrogen. More details will be reported at the presentation.

References

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[4] Kereselidze T, Noselidze I and Ogilvie J F, 2021, *MNRAS* **501** 1160–1167
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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.

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