Processes in the Early Universe and Their Cosmological Effects and Constraints

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1 Introduction

The dissertation is dedicated to nonequilibrium processes, related to the origin, chemical content and structure of Universe matter, especially its fermionic constituents - baryonic and leptonic ones, and to their cosmological role and cosmological constraints on them. The investigated processes and particles represent mainly physics Beyond Standard Models (BSMs), i.e. Electro Weak Standard Model (SM) and Standard Cosmological Model (SCM).

Such cosmological studies are actual because they provide precision information about Universe characteristics, complimentary physical information and often unique knowledge about Nature's physical laws at extreme conditions (high energy, pressure, density) unreachable at laboratories, colliders, accelerators. They also test BSMs physics. There are numerous indications for necessity of BSMs physics coming from physics experiments, astronomical observations, from theoretical and phenomenological physical, astrophysical and cosmological models. The only robust experimental detection of BSMs physics, however, are the *detection of neutrino oscillations* and the *measured value of the baryon density* (unnaturally big to be explained without new physics). Major part of the thesis is dedicated to oscillating neutrino and baryogenesis processes.

Nonequilibrium processes are not systematically studied, therefore, we explored such processes, proposing and using appropriate kinetic approach. The choice of the concrete processes and particles have been determined by the presence of abundant experimental and/or observational data and indications for their existence.

2 Main topics and results

The investigations, underlying the thesis, include mainly the study of *processes involving neutrino* ν, especially nonequilibrium electron-sterile neutrino oscillations; *processes important for Big Bang Nucleosynthesis* (BBN), defining the chemical content of the Universe baryonic component; *processes concerning Universe lepton and baryon asymmetries*; *particle creation by time-varying scalar field* and their role for reheating of the Universe, baryogenesis, formation of the very large-scale structure (LSS); *processes involving*

new particles like sterile neutrino ν_s, chiral tensor (ChT) bosons - carriers of a new interaction.

Precise description of the kinetics of the nonequilibrium processes is provided, BSMs with the additional particles and processes are constructed and numerically investigated, the cosmological influence of the new physics is determined and on the basis of astrophysical and cosmological observational data cosmological constraints on its characteristics are obtained.

2.1 BSMs processes involving neutrino and their cosmological effects and constraints

Neutrino has important astrophysical and cosmological role, and it is also important for fundamental physics theory. Due to the considerable ν influence on processes during different epochs of the Universe evolution Cosmology provides valuable information about the properties of this elusive particle and BSMs ν physics (Kiriova,Frere, 2013). Cosmic Microwave Background (CMB), LSS data and BBN put stringent constraints on ν characteristics.

In the thesis established and hypothetical BSMs neutrino characteristics were considered. The cosmological role of ν for early Universe dynamics, BBN, leptogenesis were studied. In particular, the dynamical and kinetic effects of light non-thermalized ν_s, non-equilibrium electron-sterile neutrino oscillations $\nu_e \leftrightarrow \nu_s$, effective after ν_e decoupling, ν non-equilibrium decays and possible lepton asymmetry (L) in the ν sector were investigated. [1] Besides the direct kinetic effects i.e. on pre-BBN nucleons interactions, the indirect kinetic effects of BSMs processes on BBN through neutrino oscillations were studied.

Precise kinetic equations describing the evolution of the non-equilibrium oscillating ν in the early Universe, accounting simultaneously for Universe expansion, ν oscillations and ν_e interactions with the nucleons, were derived (Kirilova, Chizhov, 1997) and used in our study. Due to the precise kinetic approach two qualitatively new effects of nonequilibrium neutrino oscillations were revealed: production of a considerable distortion in neutrino energy spectrum and neutrino-antineutrino asymmetry growth in resonant MSW $\nu_e \leftrightarrow \nu_s$ (Kirilova,Chizhov, 1997,2000,2012). Cosmological constraints on neutrino properties on the basis of astrophysical and cosmological data were obtained (Kirilova, 2014, 2015).

2.2 Processes influencing Big Bang Nucleosynthesis and their cosmological constraints

The explanation of the origin of the chemical content of the Universe by BBN is one of the great achievements of the SCM. Contemporary BBN is a very precise quantitative theory and presents precision cosmological tests of fundamental and BSMs Physics. Among primordially produced light elements He-4 is the most exactly measured element, precisely calculated

[1] In previous literature equilibrium cases were studied systematically (fast oscillations, thermalized sterile neutrino, fast thermalization of neutrino decay products, chemical potentials for the account of lepton asymmetry, etc.).

and with simple post-BBN evolution and thus it is the most appropriate for precision cosmological probe. It is the best speedometer, leptometer and also most sensitive to pre-BBN nucleons kinetics, in which ν_e participates.

We have numerically explored modified BBN models (with additional particles, and nonequilibrium processes: ν_s, $\nu_e \leftrightarrow \nu_s$, L, non-standard baryon density, etc.). The dynamical effect of discussed BSMs physics and its effects on pre-BBN kinetics and the primordial production of He-4 were analyzed. On the basis of comparison between observational data of primordially produced elements and BSMs predictions stringent BBN constraints on the number of neutrino families, L, ν_s possible characteristics, ν decay parameters and ν mass differences and mixing were derived (Kirilova,Chizhov, 1997,1998,1998a,2000; Kirilova,Panayotova,2006; Kirilova,2007,2010,2012).

In particular, in BBN with $\nu_e \leftrightarrow \nu_s$ effective after ν_e freezing production of He-4 was calculated in resonant (Kirilova,Chizhov, 1997,2000) and non-resonant (Kirilova,Chizhov, 1997,1998a) oscillation cases for the whole range of the oscillations parameters of the model, for different initial population of the ν_s state $0 \leq \delta N_s < 1$ (Kirilova,Panayotova,2006; Kirilova,2007) and $10^{-11} < L < 10^{-2}$ (Kirilova,Chizhov, 1998; Kirilova, 2012). The effect of ν spectrum distortion on BBN was shown to be several times stronger than the dynamical effect of additional ν_s. It was found that δN_s has two-fold effect on He-4: it enhances expansion rate overproducing He-4 and suppresses kinetic effects of oscillations, thus decreasing He-4 overproduction (kirilova, 2004). Isohelium contours were obtained corresponding to different helium uncertainty and different initial δN_s.

Enormous maximum overproduction of He-4 was found possible - six times bigger than in previous studies (Kirilova, 2003a). Thus, due to the precise account of neutrino oscillations effects on pre-BBN nucleons kinetic stronger cosmological constraints on $\nu_e \leftrightarrow \nu_s$ parameters than the previous BBN limits were obtained. These constraints were by orders of magnitude stronger than the corresponding experimental limits and have been obtained years before solar neutrino oscillations experiments data pointed to the preferred flavor oscillation channels (Kirilova,Chizhov, 1997, 1998a, 2000). [2]Thus, they served as an indicators for ν mixing pattern.

The dependence of BBN constraints on neutrino oscillations on the initial population of ν_s and on the value of L was studied (Kirilova, 2004, 2010, 2011, 2012). It was found that BBN constraints can be relaxed or strengthened depending on the interplay between the kinetic and dynamical effect of ν_s (Kirilova, 2007; Kirilova, Panayotova, 2006) and of L, correspondingly [3]

2.3 Processes with lepton asymmetry and its cosmological effect and constraints

Lepton asymmetry has important role in physical theories and in Cosmology. Direct measurements of L are not available, hence its indirect measure-

[2] BBN excluded two of the sterile solutions of the solar neutrino problem: large mixing angle solution (Barbieri,Dolgov, 1990) and low mixing angle solution (Kirilova,Chizhov, 2001).

[3] Previous studies considered only relaxation of BBN constraints.

ments are welcome. Cosmological constraint on L, $|L| < 0.01$, exist based on L dynamical and kinetic effect on BBN exist.

In the thesis the cosmological effects of $|L| << 0.01$ on neutrino oscillations and BBN, that have not been studied before, are explored. The interplay between neutrino oscillations and lepton asymmetry was studied (Kirilova, 2013). It was shown that small relic L, depending on its value and on ν oscillations parameters is able to suppress, enhance or stop ν oscillations. A new effect - *enhancement of* ν *oscillations by* L was discovered. The effect was caused by the phenomenon of "spectrum wave resonance", found in (Kirilova,Chizhov, 1998) due to the precise kinetic approach.

Another qualitatively new effect – *enhancement of lepton asymmetry by non-equilibrium resonant* $\nu_e \leftrightarrow \nu_s$ was found (Kirilova, Chizhov, 1997). The instability region, where the growth of asymmetry takes place was determined (Kirilova, 2012). A considerable *indirect kinetic effect of* $|L| << 10^{-2}$ (either relic or generated in neutrino oscillation) on BBN via $\nu_e \leftrightarrow \nu_s$ was found. BBN with $\nu_e \leftrightarrow \nu_s$ was shown to be most precise leptometer. Stringent cosmological constraints on L: $L < 5.10^{-4}$, due to its indirect kinetic effect on BBN were derived (Kirilova, 2011,2012).

Besides, we have numerically studied the change of BBN constraints on oscillation parameters due to L (relic or generated in $\nu_e \leftrightarrow \nu_s$). The parameter range where the constraints are strengthened, relaxed or evaded was found. Empirical relations between the values of ν oscillation parameters and L for different cases have been derived. A solution to the Dark Radiation problem was proposed.

2.4 Processes important for reheating and baryogenesis

Particle creation by a time varying scalar field

The inflationary hypothesis explains naturally and elegantly the initial conditions of the Universe in the pre-Friedmann epoch. At the end of inflation coherent oscillations of inflaton around its equilibrium point create the particles of the high energy plasma of the early Universe. Particle creation by a time varying scalar field, important for reheating, was first discussed in (Dolgov, Kirilova, 1990). Useful analytical formulae for the probability of particle creation in different cases were derived.

The role of particle creation processes by time-varying scalar field was studied and shown to be essential also for baryogenesis models (Kirilova,Chizhov 1996). Both analytical estimations and precise numerical kinetic approach for account of particle creation processes was performed (Kirilova, Panayotova, 2007).

Homogeneous SFC baryogenesis

Search for antimatter in cosmic ray (CR) and gamma ray (GR) data by ground based detectors, balloons and spacecraft provided constraints on the fraction of antimatter in our Galaxy. In our vicinity ($< 10 - 20$ Mpc) strong predominance of baryons exist, primary antibaryons have not been detected. The baryon number density is measured with high precision by BBN and CMB. It comprises $\sim 4.6\%$ of the total Universe density, and the corresponding baryon-to photon number density is $n_B/n_\gamma \sim 6.10^{-10} \sim \beta$. SCM predicts by many orders of magnitude smaller value. BSMs physics is needed to explain the observed locally baryon asymmetry β. However the

exact baryogenesis mechanism is not known, the appropriate BV and CPV processes are not detected. Different types of baryogenesis mechanisms exist, like GUT baryogenesis, electroweak baryogenesis, baryo-through-leptogenesis, Affleck-Dine baryogenesis, etc.

We explored numerically Scalar field condensate (SFC) baryogenesis model, based on the Affleck-Dine scenario (Affleck,Dine, 1985), which is among the preferred today baryogenesis scenarios compatible with inflation. The post-inflationary evolution of the SFC was followed numerically using exact kinetic equations and accounting for particle cration processes. Dependence of the produced β and its evolution on the model's parameters, namely scalar field mass, decay time, self-coupling constants, as well as Hubble constant at inflationary state and gauge coupling, were found (Panayotova,Kirilova, 2014; Kirilova,Panayotova, 2015). SFC baryogenesis model was proved successful for natural range of parameters.

2.5 Inhomogeneous SFC baryogenesis

We studied the possibility of generation of baryon inhomogeneities at large scales in inhomogeneous SFC baryogenesis models.

Inhomogeneous SFC baryogenesis and antimatter in the Universe

The existence of large quantities of antimatter at distances higher than 10-20 Mpc, corresponding to nearby clusters of galaxies is not excluded (neither by observations, nor by theory). Hence, possible mechanisms for separation between matter and antimatter domains within different inhomogeneous baryogenesis models are studied.

We tested the capability of SCF inhomogeneous baryogenesis model to produce matter and antimatter regions, safely separated by baryonically empty voids. Different possibilities of CP-violation were discussed corresponding to different size of the predicted regions and distance between them. Observational constraints on inhomogeneous models from CMB, LSS, BBN, CR and GR data and indications about the size of the antimatter domains and the distance to them were discussed (Kirilova, 2003).

Inhomogeneous SFC baryogenesis and very large-scale structure of the Universe

We investigated the possibility for the formation of the quasi-periodicity of the visible matter and the very large scale $\sim 120 - 130$ Mpc (comoving size) in the Universe in inhomogeneous SFC baryogenesis scenarios (Kirilova, Chizhov, 1996, 2000a).

2.6 Processes with new chiral tensor particles

New chiral tensor particles existence, introduced as an extension of SM (Chizhov, 1993), do not contradict the contemporary experimental data. Searches for ChT bosons are conducted at the Large Hadron Collider by ATLAS collaboration. The model with ChT particles present an extension of the fermionic component of the Universe.

In the thesis the cosmological role and place of ChT particles have been studied (Chizhov, Kirilova 2009): We explored ChT particles cosmological

influence. We determined the increase of the Hubble expansion due to introduction of ChT particles, calculated their characteristic processes and found their creation, annihilation and decay epoch and period of their efficiency in the Universe evolution. Cosmological constraint on the strength of their interaction was obtained.

In conclusion: Most of the discussed processes are among the hot topics of contemporary Physics, Astrophysics and Cosmology and their investigation and the achieved scientific results help to improve the knowledge about the physical conditions and laws of the early Universe and contribute to fundamental physics knowledge.

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