論文内容の要旨

論文題目：Energy injection from massive particles and its cosmological effects

(重い粒子の崩壊によるエネルギー放出とその宇宙論的影響)

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In modern cosmology, success of the big-bang nucleosynthesis (BBN) and existence of the cosmic microwave background (CMB) are important facts that support the standard big-bang cosmology. Predictions of the abundances of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, which had been synthesized at the end of the "first three minutes" are in good overall agreement with the primordial abundances inferred from observational data. The COBE (Cosmic Background Explorer) observations [1] showed the perfect blackbody of CMB spectrum with $T = 2.725$K. In particle physics, almost all experimental tests of the three forces described by the standard model have agreed with its predictions. However, there are still many unresolved problems in particle physics and cosmology. One of the important problems is the existence of dark matter (DM). The recent observation of WMAP (Wilkinson Microwave Anisotropy Probe) on CMB has shown that DM constitutes about 80% of the total mass in the universe [2]. Among various possibilities, supersymmetry (SUSY) is a prominent candidate for physics beyond the standard model since it possibly solves these serious problems. In particular, supersymmetric models contain a good candidate for dark matter; with R-parity conservation, the lightest superparticle (LSP) becomes stable and can be dark matter. It is widely known that, if parameters are properly chosen, relic density of the LSP agrees with the dark matter density suggested by WMAP [2]

$$\Omega_{\rm CDM}h^2 = 0.105^{+0.007}_{-0.013}, \tag{1}$$

where h is the Hubble constant in units of 100 km/sec/Mpc. This fact, as well as other motivations of supersymmetry, provides a strong motivation to consider supersymmetry as a new physics beyond the standard model.

If we consider supersymmetric models, however, several problems may also arise. In particular, in (local) supersymmetric models, superpartner of the graviton, i.e., gravitino, exists. Gravitino is a very weakly interacting particle and it may cause serious cosmological problems [3]. In the framework of string theories, there also exists various new particles, called moduli, some of which have long lifetimes and decay during or after BBN.

BBN and CMB are useful probes to these exotic particles predicted in physics beyond standard model. In fact, the prediction of BBN changes significantly if there exists an exotic massive particle with long lifetime. (Hereafter, we call such a particle X.) When the lifetime of X is longer than about 1 sec, the decay of X may induce electromagnetic and hadronic showers, which lead to photo- and hadro-dissociation of ^{4}He and subsequent non-thermal production of other light elements. Such processes may significantly change the prediction of the standard BBN scenario and, consequently, resultant abundances of light elements may conflict with observations. Furthermore, the electromagnetic energy injection causes both distortion of the CMB blackbody spectrum and modification of CMB power spectrum. As for the former, we can constrain the abundance of X since the observation [1] shows that this distortion is quite small. As for the latter, current CMB data are unable to put any constraints on the abundance of X since the modification to CMB temperature power spectrum are nearly degenerate with the primordial scalar spectral index and amplitude [4]. This degeneracy can be broken by measurement of polarization and Planck satellite [5] which will have high resolution to polarization will be launched soon. Finally, if the lifetime is very long, the spectrum of neutrinos and photons produced by the decay of X are not thermalized and may be directly observed.

In this thesis, we concentrate on scenarios in which there exists long-lived heavy particle X which dominantly decays into neutrino (and some other weakly interacting particle):

$$X \to \nu + Y, \tag{2}$$

where Y is an invisible particle which is very weakly interacting so that it does not cause any subsequent scattering with background particles. We constrain the abundance of X from various observations: BBN, CMB, diffuse neutrino flux and diffuse photon flux. In this set-up, we expect that the constrains from observations, especially BBN, are drastically relaxed. This is because the daughter particles produced by the dominant decay of X (i.e., neutrino and Y) are both weakly interacting. Here, for concreteness, we assume that the final-state neutrino is electron neutrino. (We note here that we have checked that the constraints on the properties of X are not sensitive to the flavor of the final-state neutrino.) We also presume that Y produced in the decay is a very weakly interacting particle, and that it is irrelevant for the universe. Of course, properties of X (i.e., lifetime, hadronic branching ratio, and so on) are crucially important. These properties indeed depend on the assumed set-up.

One attractive set-up is that the gravitino is the LSP and the sneutrino is the next lightest superparticle (NLSP). As other possiblity, we can consider the set-up where the LSP is axino ($\tilde{a}$) and the NLSP is sneutrino. Decay rate of this process depends on the properties of axion supermultiplet. Thus, in general, properties of X are model-dependent. Consequently, the most stringent bound may not be from BBN. For example, high energy neutrinos emitted in the X particle decay was considered in [6] where the upper bounds on the X abundance were obtained from nucleon-decay detectors and Fly's Eye air shower array.

The decay of X may induce electromagnetic and hadronic showers, which can have significant influence on many observations of the universe. The time evolution of electromagnetic and hadronic showers can be calculated by the numerical approach of [7]. The remaining work is only to specify the initial spectra of charged particles and photons created by the decay of X. However, it is rather difficult and complex in our case compared with in the case where charged particle or photon is produced by the main decay mode. There are two reasons. One reason is that we have to know how much energy of the emitted neutrino converts to visible energy. High energy neutrino scatters off off background neutrinos and electrons (positrons), and creates charged leptons and pions with gradually losing its energy. In order to estimate the initial spectra, we have numerically solved the Boltzmann equation describing the time evolution of the high energy neutrino spectrum taking into account of all relevant processes. The other reason is that other subdominant decay channels should be taken into consideration. This is because the constraints from the main decay mode Eq. (2) is quite weak so that other subdominant decay channels which contain electronic and hadronic may be important. Even though the dominant decay mode is the two-body process, one should keep in mind that decay chennels with three- and/or four-body final state should also exist since the neutrino as well as X and/or Y couple to Z- and W-bosons. The emitted (real or virtual) weak bosons subsequently decay into quarks and leptons. With this type of three- and/or four-body decay processes, energetic quarks and charged leptons are produced. Therefore, we have to calculate the spectra of charged leptons and photons which are finally produced by these subdominant decay channels.

As an important application of our study, we consider cosmological constraints on models where (1) the sneutrino is the NLSP, and (2) the gravitino is the LSP. The most probable candidate for NLSP is usually considered to be neutralino or stau with the case where the gravitino is LSP. Recent detailed analysis, however, have shown that these models are seriously constrained from BBN [8, 9]. To the contrary, we expect that the constrains from BBN are drastically relaxed in our model since the dominant decay mode produces particles which are both weakly interacting. In addition, we also investigate the implication of this scenario for thermal leptogenesis. It is widely known that the present baryon asymmetry of the universe may originate from non-equibrium decay of right-handed (s)neutrino which has frozen out from the thermal bath [10]. Our model can be compatible with the thermal leptogenesis in a larger parameter space than other scenarios like stau NLSP.

Finally, we have carried out the precise estimation of how much initial energy of incident electron/photon converts to heat, excitation and ionization with taking the Hubble expansion into account. This calculation is crucial to estimate the change of the ionization history and CMB power spectrum induced by high energy particles. However, there has been no studies of this topic yet. This is because it is very difficult to solve Boltzmann equations for energetic electron/photon. We have resolved it by the improvement of the method which has been used for the calculation of the energy deposition of energetic electrons in partially ionized gas [11, 12]. Our result can apply not only to the decay of X, but to whatever situations, for example DM annihilation. For one application, thus, we constrain the thermally averaged cross section for DM annihilation with the optical depth obtained by WMAP [13].

References

[1] J. C. Mather et al., Astrophys. J. **420**, 439 (1994).

[2] D. N. Spergel et. al., Astrophys. J. Suppl. **170**, 377 (2007).

[3] S. Weinberg, Phys. Rev. Lett. **48**, 1303 (1982).

[4] N. Padmanabhan and D. P. Finkbeiner, Phys. Rev. **D72**, 023508 (2005).

[5] http://www.esa.int/science/planck

[6] P. Gondolo, G. Gelmini and S. Sarkar, Nucl. Phys. B **392**, 111 (1993)

[7] M. Kawasaki, K. Kohri and T. Moroi, Phys. Lett. B **625**, 7 (2005); Phys. Rev. D **71**, 083502 (2005)

[8] J. L. Feng, S. f. Su and F. Takayama, Phys. Rev. D **70**, 063514 (2004); Phys. Rev. D **70**, 075019 (2004).

[9] F. D. Steffen, JCAP. **0609**, 001 (2006).

[10] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).

[11] L. R. Peterson, Phys. Rev. **187**, 105 (1969).

[12] A. Dalgarno and G. Lejeune, Planet. Space Sci., **19**, 1653 (1971).

[13] J. Dunkley et. al., arXiv:0803.0586