

Opening Remarks ~ Prospects of very high energy cosmic ray interactions for astroparticle physics

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Abstract. Hadronic interactions of very high energy cosmic rays have been studied in various aspects of motivation. In recent decades, mainly motivated by air shower experiments, modelling of very high energy cosmic ray interactions have been greatly improved together with new data obtained from high energy colliders such as the LHC. Regarding recent rapid progress of multi-messenger astronomy, a precise knowledge on secondary particle production by cosmic rays at very high energy is largely indispensable. This would give us a new insight and new motivation to study minimum bias hadronic interactions of very high energy cosmic rays.

1 Introduction

Cosmic rays always motivate us to study unrevealed nature. In 1960s-70s, there was a great interest in high energy hadronic interactions by cosmic ray experiments to reveal the mechanism of multi-particle production at very high energies before large accelerators were built [1]. There were various models such as the hydrodynamical models [2] or the fireball models [3, 4] discussed to explain hadron production from ultra-relativistic collisions, which was tested only by cosmic ray interactions at that moment. Some of the initial ideas would invoke an idea of quark-gluon plasma discovered at heavy-ion colliders after several decades.

Precise modelling of very high energy cosmic ray interactions became more important to understand their origins by the extensive air-shower experiments. The energies or chemical composition of cosmic rays can be deduced from the observation of secondary particles in the air showers. The precision of the measurement depends on the accuracy of modelling air shower development where minimum-bias hadronic interactions at very high energy play an essential role. In this context, several air shower Monte Carlo simulation packages such as CORSIKA [5] or COSMOS [6] have been developed as well as phenomenological cosmic ray interaction models dedicated for very high energy interactions such as SYBILL [7], QGSJETII [8], DPMJET3 [9], EPOS [10], besides PYTHIA [11] are often used as standard hadron interaction models in accelerator experiments. These models have been tested and well-tuned with recent various measurements done in the Large Hadron collider (LHC) at collision energies up to $\sqrt{s} = 13$ TeV equivalent to $\sim 10^{17}$ eV in the laboratory frame.

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2 Some legacy in Nagoya University for cosmic ray astronomy

Here some historical connections of Nagoya University to this symposium are given.

Nagoya University had contributed to a very early stage of cosmic ray astronomy. Prof. Yataro Sekido moved from Nishina-lab. in Riken to Nagoya University in 1945, and started his cosmic ray lab aiming to reveal origins of cosmic rays by cosmic ray telescopes. He built a series of Nagoya muon telescopes to explore the direction of a possible excess [12]. Due to the existence of inter-stellar magnetic fields, which was yet unknown at that moment, it was apparently impossible to detect any positive signals of cosmic ray origin even with his largest Nagoya muon telescope No.3, which was built in 1960 as a large binocular of 18-m long air-Cherenkov telescopes mounted on an altazimuth mount. His study, however, connects to one of the most early works on cosmic ray anisotropy in heliospheric physics.

At the same time, Prof. Sachio Hayakawa moved to Nagoya University in 1959 and proposed γ -ray astronomy, which is one of the most early attempts for astroparticle physics [13]. He also started a lab for X-ray observation in the university, and finally made a great effort to initiate a gravitational wave observatory in Japan, and promote multi-messenger astroparticle physics in the university and in Japan until his sudden death in 1992 as a president of the university.

Prof. Kiyoshi Niu is known as one of those who proposed the two-fireball model in 1958, and he had made continuous efforts to understand multi-particle production at very high energy cosmic ray interactions with the nuclear emulsion technique. He developed the Emulsion Cloud Chamber (ECC) and introduced the first automated scanning system adopted for nuclear emulsion analyses. After he moved to Nagoya University in 1971, he in-

tensively studied hadron jet production in ECC on-board aeroplanes and discovered the famous "kink" of Niu's X-particle decays, later known as charmed particles [14]. He continued to summarize his fireball model until quite recently inspired by recent progress of cosmic ray interaction models and LHC data, but unfortunately passed away in 2017 just one year before ISVHECRI 2018.

3 Cosmic ray interactions for multi-messenger astrophysics

Several years ago, the first observation of high energy astrophysical neutrinos at sub-PeV energies announced by IceCube has opened neutrino astronomy. Together with well-established γ -ray astronomy in the MeV to TeV energy range, a new era of multi-messenger astronomy is now launched [15]. In addition, recent discovery of gravitational wave events and the first identification of associated electromagnetic emissions from the merger of neutron stars [16] dramatically expands the richness of this field.

Legacy of state-of-art cosmic ray interaction models at very high energy can also substantially contribute to develop the field through the improvement of calculations for the production of astrophysical neutrinos or γ -rays, the messengers from hadronic origins. Neutrinos or γ -rays from charged π -decays typically carry one-tenth of the primary cosmic ray energy. Therefore sub-PeV neutrinos are produced by PeV primary protons. On the other hand, precision measurements of astrophysical γ -rays are foreseen at future air Cherenkov telescopes such as CTA. Also the 100-TeV γ -ray sky is now being explored by air-shower arrays in order to identify cosmic PeVatron sources.

It is also relevant to indirect dark matter searches using not only γ -rays but also anti-particles such as positrons or anti-protons. Several space-borne experiments such as AMS-02, Pamela, CALET and DAMPE are observing the cosmic positron flux in the region of a few 100 GeV, which might be a hit for dark matter annihilations or decay [17]. AMS-02 also explores dark matter signal in the anti-proton spectrum in the region of a few 100 GeV. Here uncertainties of the background spectrum predicted by cosmic ray interaction models is a key to identify the possible excess [18]. To reduce the uncertainty in the production of anti-protons via p -He collisions at such energies, measurements have been done using a He-gas injection target exposed with a 7 TeV proton beam at the LHC [19]. The precise modelling of γ -ray energy spectra or yields of anti-particles produced by very high energy protons colliding with the inter-stellar medium has great importance to interpret the observations [20].

Precise modelling of neutrino production is another challenge. Because gigantic neutrino detectors always suffer by background atmospheric neutrinos, both modelling for signal (astrophysical) and background (atmospheric) are needed. In the high energy region, not only π -decays but also K -decays substantially contribute to the neutrino flux. Production of strange particles in the forward region is uncertain, while measurement at high energy colliders

are indispensable. Moreover, the prompt neutrino component from charm decays is largely unknown because there is a lack of experimental data for forward charm production. Several attempts to measure charm production in the forward regions are now ongoing at the LHC [21]. It is also important to improve the modelling of the atmospheric neutrino flux in the lower energy region relevant to neutrino oscillation studies.

4 Conclusion

Very high energy cosmic ray interactions have been studied in various interests, while they give a unique opportunity to study very high energy phenomena which may not be accessible even at existing accelerators. A new insight and motivation is derived from the recent rapid progress of astroparticle physics in the multi-messenger era to improve the knowledge on their production and propagation. It implies that the study of very high energy cosmic ray interactions is important as it turns into the precision phase from the discovery phase, although there would still be room for new phenomena such as chiral restoration, etc. This field is essentially multi-disciplinary and therefore a more variety of study is foreseen.

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