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Proton and Helium spectra obtained by RUNJOB experiment

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This report presents the final results of the proton and the helium spectra in the energy range between 10 and 500 TeV/nucleon obtained by RUNJOB experiments as trans-Siverian long duration balloon. A proton with PeV energy was directly detected in 1995 campaign. This is the first detection of proton event more than 10^{15} eV in direct observation. Our proton spectrum is in good agreement with other results such as JACEE and SOKOL, but the intensity of the helium component is nearly half that obtained by them, while it agrees with MUBEE. The slopes of the spectra of these two elements in RUNJOB are almost parallel with power index of 2.7–2.8 in the energy range 10–500 TeV/nucleon. These results suggests simply acceleration and propagation mechanism of cosmic rays depending on particle rigidity.

1. Introduction

Proton and helium elements are the most predominant cosmic-ray (CR) components over the wide energy ranges, providing us the reliable energy spectra with rich statistics as compared with other heavier elements. These two components give us a vital clue for the understanding of the acceleration mechanism of CRs and their propagation processes in the Galaxy. The energy dependence of the flux ratio, helium/proton, brings us important information, for instance the contribution of the reacceleration during the propagation might appear in the low energy region around 1 GeV/nucleon [1], and the non-linear effect in the shock acceleration in the source might be observed in the higher energy region $\gtrsim$ 100 GeV/nucleon [2]. It is also quite interesting and critical if the acceleration limit appears in the proton spectrum somewhere around 1 PeV, and the helium component becomes abundant after the drop of the proton spectrum. However, there were some observations in the energy region more than 100 GeV/nucleon, particularly a few ones in several hundreds TeV region with small statistics, in which are removed troublesome effects such as the ionization loss, solar modulation, the complicated energy-dependent collision cross section and so forth.

With these backgrounds, we commenced a joint balloon experiment with use of the emulsion chambers in 1995. Eleven balloon flights have been launched from the Kamchatka peninsula since then and ten of them were successfully recovered near the Volga region after a level flight of ∼150 hrs. One balloon as RUNJOB-VII failed due to the malfunction of the auto-safety system. The total exposure of these campaigns amounts to 575 m^2hrs, with an average flight altitude of ∼ 32 km corresponding to ∼10 g/cm^2 of atmospheric depth.

This paper is focused only to the final results of proton and helium spectra based on full exposure of RUNJOB flights except for RUNJOB-VII, while we omit the technical details because of reporting them in Apanasenko et al.(2001)[3] as the flight performance, such as the trajectories and the altitude variations of RUNJOB balloons (see also Furukawa et al., 2003 [4]), and detailed descriptions of analysis procedures such as the chamber efficiency, energy determination (see also Hareyama et al., 2003 [5]) , charge determination, and so on. The heavy components and all particle spectra by our experiment were presented in the other report by Ichimura et al. for heavy components [6] and Sveshnikova et al. for all particle spectrum and avarage mass [7] in the same session of this proceedings and see also Derbina et al. [8].

2. Results and Discussion

In Figure 1, we demonstrate the proton and the helium spectra obtained by our ten flights together with the results of other measurements such as JACEE [9], SOKOL [10] and MUBEE [11] in the same energy range as RUNJOB, where the vertical axis is multiplied by $E_0^{2.75}$ in order to emphasize spectral features. Also shown are the results at lower energies obtained by AMS [12, 13], BESS [14] and IMAX [15]. The later groups provide remarkable spectra with excellent energy resolution and high statistics, although the energy region of 0.5–100 GeV/nucleon does not cover the energy region of our interest here. Their spectra appear to continue smoothly to energies of $\gtrsim$ 1 TeV/nucelon, although we can not conclude whether the extrapolation of their helium spectra is more likely to connect to the RUNJOB or JACEE plots.

We note that a PeV-proton was detected in the first 1995 flight, but no new proton with PeV energy has been observed in other flights. This proton detected directly is the first directly evidence to be accelerated to PeV/nucleon energy. Secondary, our helium intensity is nearly half of those given by JACEE and SOKOL, while consistent with MUBEE. Therefore, the slopes of our proton and the helium spectra are nearly parallel, with indices of 2.74±0.08 and 2.78±0.20 in the energy range less than 100 TeV/nucleon, respectively, where the errors are statistical only.

In order to see the later result more distinctly, we show the energy dependence of the helium-to-proton flux ratio over the very wide energy range 500 MeV/nucleon to 100 TeV/nucleon in Figure 2. A discrepancy in the lower energy region, $\lesssim$ 10 GeV/nucleon, is apparent between AMS, BESS and IMAX, but this is simply due to the different period in the solar activity of each experiment. The change in the ratio at lower energies, $\lesssim$ 10 GeV/nucleon, may be due to the re-acceleration effect, which must be significant for lighter elements such as protons and helium which have much longer collision mean free path than the escape length from the Galaxy, whereas it would not be so important for heavier elements [1].

It is clear that the RUNJOB plots lie on the extrapolation from those in the lower energy data with a constant value ∼ 0.05, while the JACEE [16] data suggest the ratio increases gradually with energy, reaching ∼ 0.15 at 100 TeV/nucleon. The RUNJOB result seems to match the current understanding of the shock acceleration mechanism in supernova remnant which depends only on the particle rigidity, while the JACEE result are unexpected from these expectations. So the discrepancy between JACEE/SOKOL and RUNJOB/MUBEE is

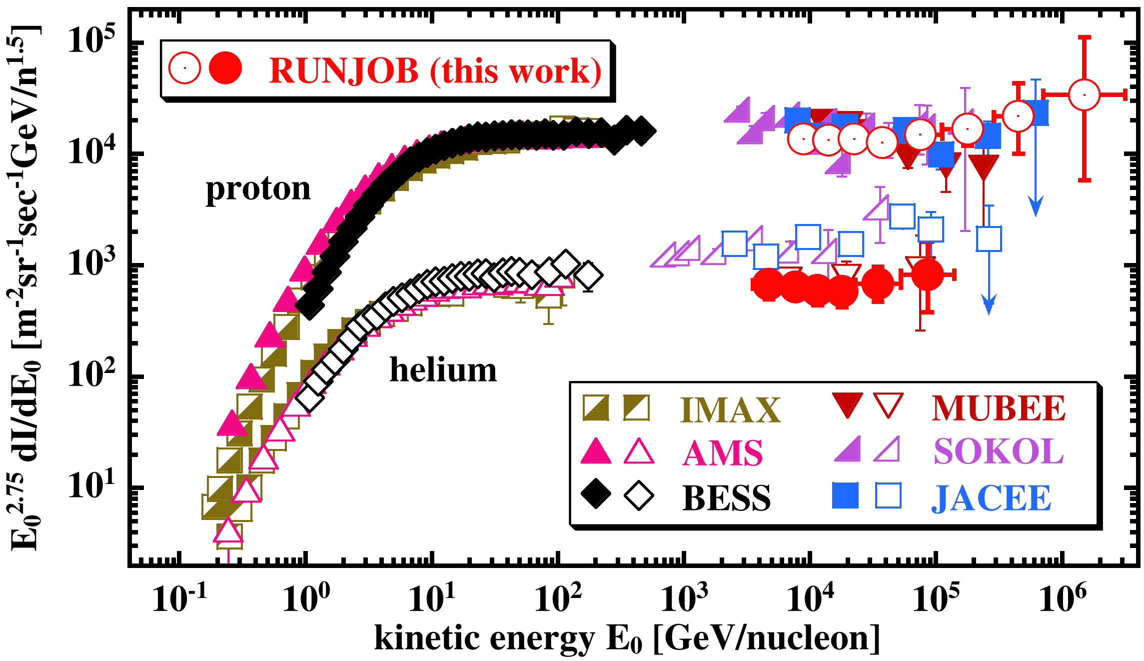

Figure 1. Proton and Helium spectra obtained by full data of RUNJOB experiment(open and filled circle) together with other direct observations[9, 10, 11, 12, 13, 14, 15].

critical for our understanding of the origin of CR and the acceleration mechanism, with these two sets of results leading to quite different alternatives.

3. Conclusion

The proton and the helium spectra and thier ratio, helium/proton, were presented in this report that based on full data in the energy range between 10 and 500 TeV/nucleon observed by RUNJOB experiment. The both spectra are almost palarell with power index of $\sim$2.75 and the ratio is constant with value $\sim$0.05 lying on the extrapolation line from those in the lower enegies. Moreover we observed a proton with PeV energy directly. These results suggest the acceleration and propagation process of CRs depend on its rigidity, though the statistics more than 100 TeV/nucelon is not enough to discuss the acceleration limit by supernovae. In future, we need some direct observations in the energy range between 10^{14} and 10^{16} to clear the acceleration limit connecting “knee” problem.

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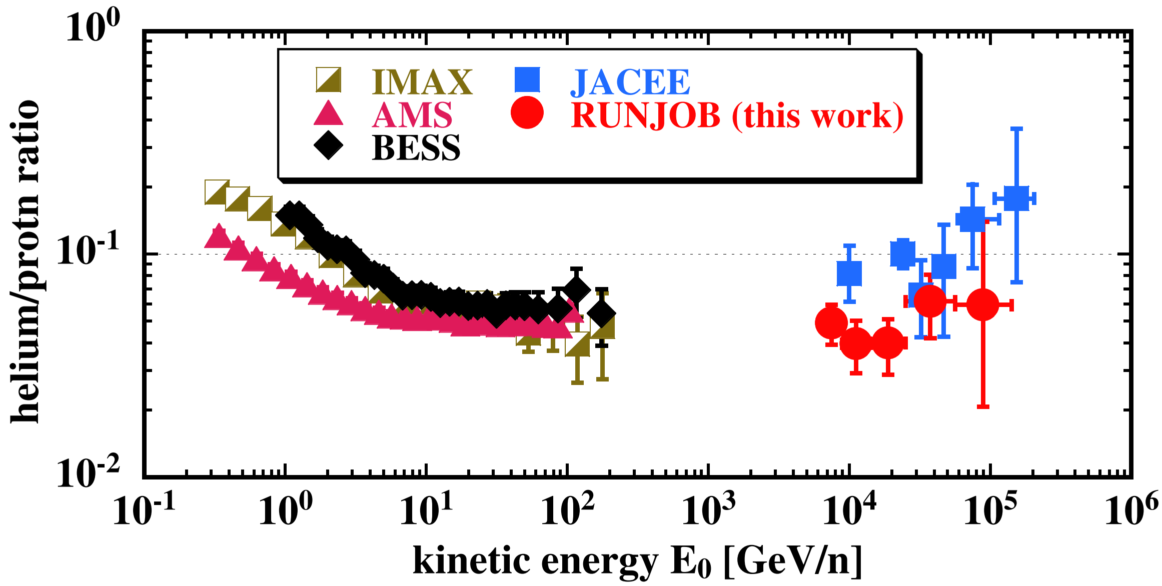

Figure 2. The ratio of proton to helium fluxes obtained by full data of RUNJOB experiment(filled circle) with other direct measurements as AMS, BESS, IMAX and JACEE[16]. The AMS , BESS and IMAX data are cluculated by one of authors, M.H, from thier papers [12, 13, 14, 15].

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