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Heavy component spectra and secondary to primary ratios obtained by RUNJOB experiment

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RUNJOB final results on the energy spectra of primary heavy cosmic ray components are presented. Data are from ten RUNJOB campaigns performed from 1995 through 1999. And the energy spectra of CNO, NeMgSi and Fe groups are shown here as well as the energy dependence of the secondary/primary ratio.
We find our heavy component spectra are in agreement with the extrapolation from those at lower energies obtained by CRN (Chicago group), monotonically decreasing with energy, in contrast to JACEE and SOKOL data, which indicated a gradual increase with energy, particularly for the CNO group at $\gtrsim 5$ TeV/nucleon.
As for the secondary to primary ratio we have observed in TeV/nucleon energy region, it is difficult to determine the energy dependence of their average path lengths by the RUNJOB data only, because the large uncertainty of atmospheric corrections due to the poor statistics exists.

1. Introduction

Heavy primaries in cosmic rays provide us additional informations to those from protons and alpha primaries. Heavy components of cosmic rays are created in the thermonuclear fusion process in the star, though protons and helium nuclei were produced at the beginning of the universe. So heavy components carry more informations on the origin of cosmic rays. Moreover, the nuclei which are not created in the star tells us the galactic space through which the cosmic rays propagate. To analyze the propagation of cosmic rays, the leaky box model with the energy dependent escape length has been often used, but it would be unrealistic in the higher energy region. So observation at the higher energy region is essential to check the models of the propagations. RUNJOB data is important to infer the propagation models, though statistics is still poor.

2. Results and Discussion

We give the energy spectra of the three heavy-primary groups, CNO, NeMgSi, and Fe, in Figure 1, where the filled red symbols denote RUNJOB data, and other data, HEAO-3[1], SANRIKU[2], CRN[3],[4], SOKOL[5] and JACEE[6] are also plotted. The vertical axis is multiplied by $E_0^{2.5}$. One should remember here that the JACEE data for iron include the sub-iron components with $Z = 17 - 25$, while those from RUNJOB are for pure iron only.

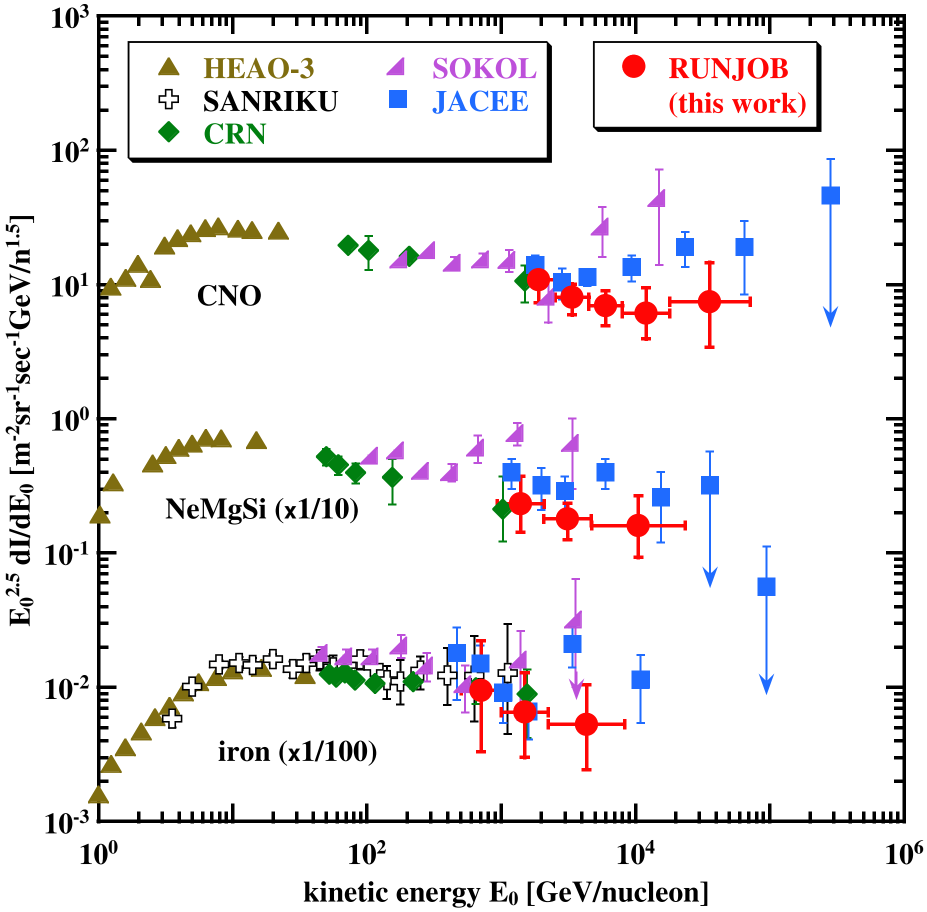

Figure 1. Heavy component spectra obtained by RUNJOB (filled red) together with other direct measurements. The intensities are multiplied by 1/10 for the NeMgSi-group and 1/100 for the iron-group, respectively.

The RUNJOB data appear to be consistent with the extrapolation of CRN data in the lower energy region, whereas the JACEE and SOKOL data seem to increase gradually in the higher energy region, particularly for the CNO group.

Taking the data of RUNJOB and CRN alone, the energy spectra of heavy components decrease monotonically with energy up to ~ 10 TeV/nucleon, and the slope of the energy spectrum becomes gradually harder with heavier mass, for instance ~ 2.7 for the CNO group and ~ 2.6 for Fe. The paper of p-He spectra by RUNJOB in this proceedings shows that the slope of proton and helium spectra is $2.7 \sim 2.8$. Thus the gradual change in the slope of the energy spectra of the individual elements indicates a rigidity-dependent form. This result is a natural consequence of the different collision cross-sections, with, for instance, ~ 40 mb for p–p and ~ 750 mb for Fe–p in the TeV region. This could be explained by the following possible scenarios; the stochastic shock acceleration at supernova blast waves, and the leakage from the Galaxy in the propagation process, both of which depend on the particle rigidity [7].

On the other hand, if JACEE and SOKOL data are true, we must find an alternative scenario, in relation to the source and the acceleration mechanism. In fact, as several authors have pointed out, based on JACEE data the source of helium and heavier components must be different from that of protons, and could, for example, be produced by supernova shocks expanding into Wolf-Rayet winds [8], [9], [10].

In Figure 2, we show the secondary/primary ratio obtained by the present work together with other data, ACE/CRIS[11], HEAO-3[12], [1] and SANRIKU[13], covering the lower energy region. One should recall, however, that the balloon altitude in RUNJOB of $\sim 10\,\mathrm{g/cm^2}$ results in a considerable contamination effect for these secondary components, coming from the fragmentation products in the atmosphere. We have eliminated contaminations of 45% for the sub-Fe components and 67% for the LiBeB group in Figure 2, with the details of these calculations appearing in the reference [14], which summarizes the simulation procedure and explicit values of the fragmentation parameter for various projectile nuclei in the atmosphere. So the RUNJOB data in Figure 2 need to be viewed with these uncertainties in mind, and we reserve a definite conclusion for the future study.

3. Conclusion

We have discussed the spectra of heavy components, combining the data from RUNJOB and CRN, but it is apparent to require the single experiment to cover this energy region with suitable statistics.

Admitting the poor statistics and the uncertainty of atmospheric corrections, we would point out that our RUNJOB observations of 2ry/1ry ratio may not lie on the extrapolation of the lower energy data. It indicates the simple leaky box model with the decreasing escape length for the rigidity may not work in higher energy region. More certain data is required to draw the definite conclusion as said before.

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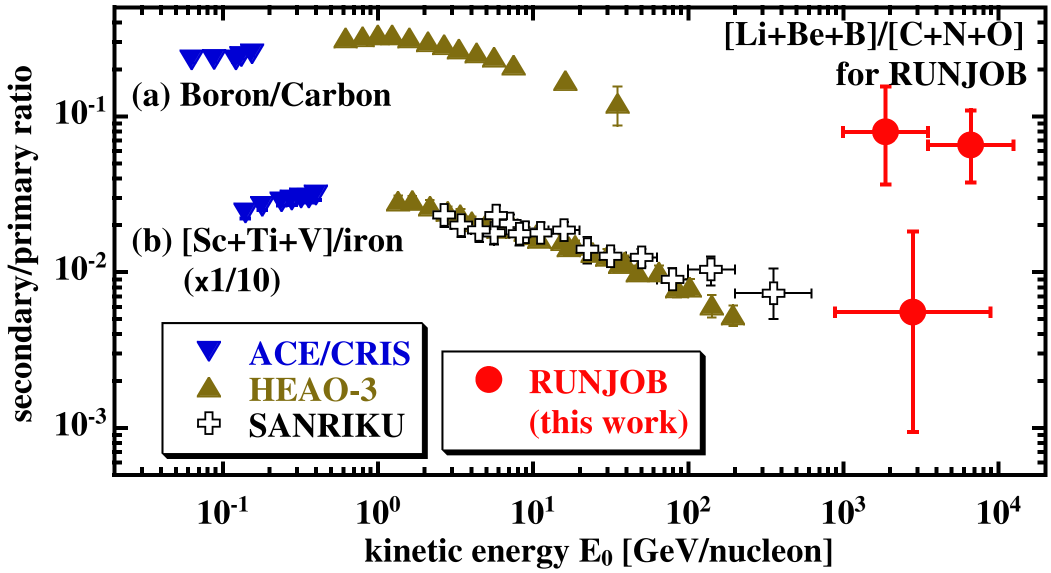

Figure 2. Secondary to primary ratios for (a) B/C and (b) sub-Fe/Fe, where RUNJOB data give [LiBeB]/[CNO] in place of B/C, and sub-Fe represents $Z = 21 - 23$.

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