The high precision observation of ultra heavy cosmic ray nuclei

Nobuyuki Hasebe, Tadayoshi Doke, Makoto Hareyama, Satoshi Kodaira, Takashi Miyachi, Mitsuhiro Miyajima, Osamu Okudaira, Kunitomo Sakurai, Masatoshi Takano, Shoji Torii, Naoyuki Yamashita, Nakahiro Yasuda, Hiroko Tawara, Shogo Nakamura, Koichi Ogura, and Hiroshi Shibuya

***Abstract*— The high precision observation program of ultra heavy cosmic ray nuclei is proposed as the new approach of long duration balloon and space station experiments to measure nuclear composition of galactic cosmic rays. It consists of two kinds of large telescopes, a Large Heavy Isotope Telescope Array (LHITA) and a Large Area Heavy Particle Spectrometer (LAHPS) which are made of solid-state track detectors, BP-1 and CR-39. They focus on the precise measurement of elemental and isotopic abundances of ultra-heavy particles in cosmic ray source region, which covers a wide range of scientific themes including studies to understand the origin, the mechanism of heating and initial acceleration of charged particles, and to investigate the nucleosynthesis of ultra-heavy nuclei by *s*-, *r*- and *p*-process and the chemical evolution of galactic matter. In order to pursue these objectives, three observations are planned in International Space Station and long duration balloon experiments in southern hemisphere for relativistic ultra-heavy cosmic rays ($Z \leq 82$) and up to actinides by LAHPS, respectively. LHITA onboard Antarctic balloon will observe an elemental and isotopic composition Fe~Ba in the energy range from 100 MeV/n to 500 MeV/n. We will also search for the existence of trans-uranium atoms in relativistic cosmic rays. These telescopes have an unprecedented collection power about 10 times larger than the previous ones.**

***Index Terms*—Ultra heavy nuclei, Galactic cosmic rays, Chemical composition, Solid-state track detector**

I. INTRODUCTION

Our galaxy is filled with various relativistic nuclei and electrons. The source of the galactic cosmic ray (GCR) nuclei is still unknown. However, GCRs are thought to be accelerated by supernova (SN) shocks in the interstellar medium (ISM). The location of SNs are not distributed randomly in the Galaxy, but explode preferentially in OB-associations which have been the site of massive star formation and in which hot and young stars are abundant [1,2]. An SN explosion in an OB association forms a shock into a local ISM which is enriched in freshly synthesized material from previous SNs. Recently, the Cosmic Ray Isotope Spectrometer (CRIS) measurement of Fe-Co-Ni isotopes by the Advanced Composition Explorer (ACE) tells us that the average time delay between nucleosynthesis and acceleration is greater than about 10^5 years [3].

Elemental abundance in the cosmic radiation above Z = 30 has been measured by experiments of ARIEL-6 [4], HEAO-3 [5], and recent experiments of TREK [6] and TIGER [7]. The abundance of even-Z nuclei extending from Z = 30 to 60 has been individually resolved. For $Z \geq 60$, since the statistics are low in quality and the charge resolution is broadened in the HEAO-3 and ARIEL-6 data, the grouping of charges was necessary for meaningful abundance measurements. Those results for $Z \geq 60$ are enhanced in *r*-process elements at the source. However, such an enhancement among elements with $Z \geq 60$ is complicated by elemental fractionation process. The isotopic measurement provides a distinct advantage in determining the mixing ratios of the *s*- to *r*-process products, because those ratios are immune to elemental fractionation processes. And we still lack definitive data for elements $Z \geq 30$ that could provide further understanding of the origin and history of galactic matter. Measurements of GCR composition beyond the iron peak are of special interest because of their information about neutron-capture nucleosynthesis processes and because of a number of stable and radioactive species contained in them.

The next step beyond ACE/CRIS [8] is to measure individual isotopes with an excellent mass resolution and a high statistics for elements with $58 \geq Z \geq 30$, and to measure Pt-Pb group nuclides and actinides with an excellent charge resolution and a high statistics by the use of particle spectrometers with at least two orders of magnitude increase in collecting power.

In this paper, we focus nuclear composition of the ultraheavy galactic cosmic rays (UH-GCRs) and present the observation

N. Hasebe, T. Doke, M. Hareyama, S. Kodaira, T. Miyachi, M. Miyajima, O. Okudaira, K. Sakurai, S. Torii, M. Takano, and N. Yamashita are with Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan (corresponding author to provide phone: +81-3-5286-3897; fax: +81-3-5286-3897; e-mail: nhasebe@waseda.jp, N. Hasebe).

N. Yasuda is with National Institute of Radiological Sciences, Inage, Chiba 263-8555, Japan

H. Tawara is with High Energy Accelerator Organization, Tsukuba, Ibaraki 305-0801, Japan

S. Nakamura is with Department of Physics, Yokohama National University, Yokohama, Kanagawa 240-8501, Japan

K. Ogura is with College of Industrial Technology, Nihon University, Narashino, Chiba 275-8576, Japan

H. Shibuya is with Department of Physics, Faculty of Science, Toho University, Funabashi, Chiba 274-8510, Japan

program of isotopic and elemental compositions of UH-GCRs for Z≥30 with the energy above several 100 MeV/nucleon by means of an extremely large spectrometer array made of solid-state track detectors (SSTD) onboard International Space Station, long duration super-pressure balloon over Antarctica or Southern hemisphere.

II. Scientific Significance For the observation of elements and isotopes in UH-GCRs

Comparison of the GCR source (GCRS) abundance obtained with the solar system (SS) abundance indicates that UH composition in GCRs with high condensation temperature is relatively enhanced to the SS abundance (see Fig. 1) [9,10]. This tendency is explained that the multiple supernova (SN) shocks in OB-association can accelerate the GCRs from seed nuclei originated from dust-grains drifting in interstellar medium which condensed rapidly after an SN explosion [10,11]. The element ^{22}Ne in GCRS abundance is enhanced relatively as compared with SS abundance from the previous observations of isotopic compositions for Z<30 based on most recent experiment ACE/CRIS [12]. This is thought as due to the contribution from Wolf-Rayet stars which usually exist in superbubble [12,13]. The measurement of the abundances of ^{59}Ni and ^{59}Co gives the average delay time greater than about 10^5 years between nucleosynthesis and acceleration, and suggests that the SN does not instantly accelerate their own ejecta [3]. Moreover, the trans-iron nuclei are produced by the process different from the one approximately to the nuclei lighter than iron-group ones. Although the elemental composition of UH-GCRs was measured by some experiments [4-7], the measured one is modified by the elemental fractionation effect. The isotopes produced by only *s*, *r*, *p*-process such as ^{92}Mo, ^{96}Mo, ^{100}Mo will thus be useful for the understanding of GCR origin. In particular, the isotopes produced by only *r* and *p*-process are specifically distinguished because the mass number of adjacent isotopes are separated by two atomic mass units.

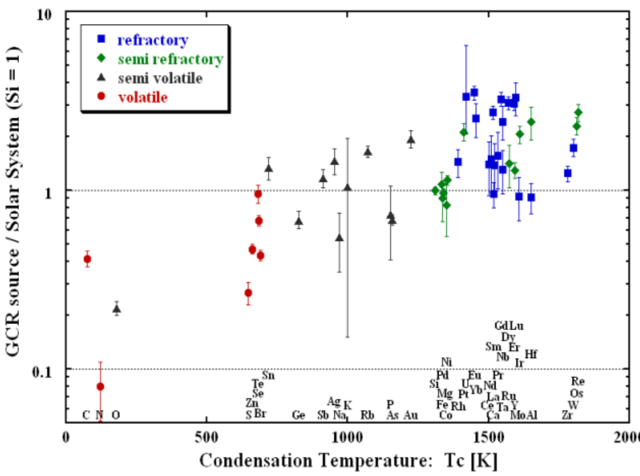

Fig. 1. The source composition of GCRs relative to the SS abundance for their condensation temperatures [10].

The problem of injection mechanism still remains whether GCRs are initially accelerated by FIP (First Ionization Potential) or Volatility one. Meyer et al. pointed out that there are some elements (Ge, Rb, Sn, Cs, Pb, Bi) without the correlation between FIP and Volatility [14]. Comparison their GCRS abundances with SS abundances in the broad range of chemical elements will resolve the injection mechanism.

The comparison of the abundance in the source of GCRs (mean life time: about 10^7 year) with those in primitive metal-poor star (about 10^{10} yr ago) or solar-system (4.5×10^9 yr ago) seems useful for understanding of the chemical evolution of the Galaxy.

Using the radioactive isotopes and actinide elements in UH-GCRs, we will be able to determine the GCRs life time with ^{127}I ($\tau_{1/2} = 1.7\times10^7$ yr), ^{135}Cs ($\tau_{1/2} = 2.1\times10^6$ yr), ^{247}Cm ($\tau_{1/2} = 1.6\times10^7$ yr), the delay time between nucleosynthesis and acceleration with ^{81}Kr ($\tau_{1/2} = 2.3\times10^5$ yr), and search for the nearby source due to SN explosion with ^{79}Se ($\tau_{1/2} = 6.5\times10^5$ yr) or ^{93}Zr ($\tau_{1/2} = 1.5\times10^6$ yr).

In addition, we may find superheavy nuclei like trans-Uranium nuclei in GCRs by the extremely large acceptance of our GCR telescope. It is predicted that such extremely massive particles should exist in “island of stability" which corresponds to the region of predicted neutron magic number of *N*=184 [15].

Thus, the observation of elements and isotopes for Z≥30 will enable to make a great progress in the studies of the origin of GCRs, the stellar nucleosynthesis, the chemical evolution of out galaxy and GCR injection, acceleration and propagation mechanisms.

III. Detector Concept

The solid-state track detector (SSTD) such as CR-39 plastic detector and BP-1 glass detector is very promising for the large-scale observation of these nuclei in space. This is due to the fact that it is easy to fabricate a low-cost large detector array. We plan to observe isotopic composition of 58≥Z≥30 with the energy of < 500 MeV/n and elemental composition up to actinide elements in the relativistic energy region. In order to observe these compositions, we plan two kinds of large telescopes, a Large Heavy Isotope Telescope Array (LHITA) and a Large Area Heavy Particle Spectrometer (LAHPS) which consist of SSTD.

LHITA is designed to measure the isotopic composition of UH-GCRs. The incident particles of Z≥30 with the energy (top of instrument) < 500 MeV/n should be stopped in LHITA to identify its mass. Figure 2 and Table 1 show the schematic drawing and the characteristics of LHITA instrument, respectively. Only track stopped in instrument is selected and then analyzed to measure its mass. On the other hand, LAHPS is designed to measure the elemental composition of UH-GCRs. Figure 3 and Table 2 show the schematic drawing and the characteristics of LAHPS instrument, respectively. There are

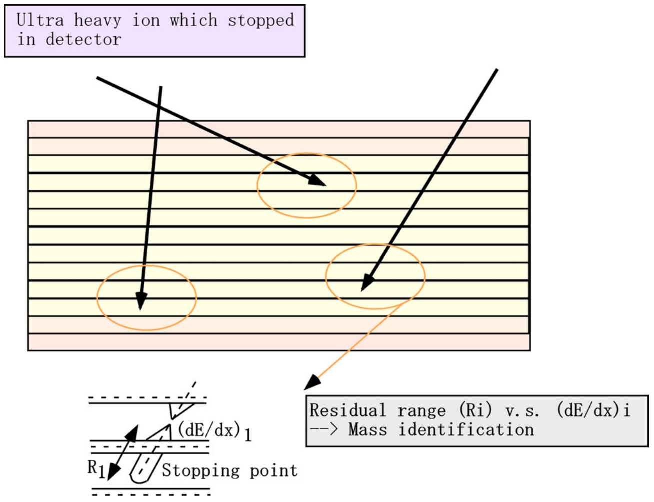

Fig. 2. Schematic drawing of LHITA instrument. Only track stopped in instrument is selected and then analyzed to measure its mass. Ion mass is determined using the relationship between residual range and deposited energy in detector.

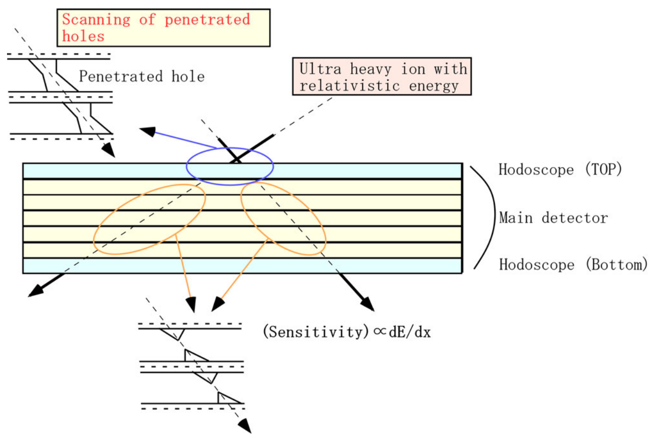

Fig. 3. Schematic drawing of LHAPS instrument. There are the hodoscopes at the top and bottom of instrument, which select only UH particle with the relativistic energy passed through the instrument and determine their trajectories by searching for their through-holes. energy in detector. Nuclear charge of particle is determined using the track registration sensitivity which is a function of energy loss in detector.

Module size	25 cm × 25 cm × 5 cm
Number of module	8 × 8 modules
Total size	2.0 m × 2.0 m × 0.05 m
Total Weight	400 kg +
Geometric factor	~ 3 m^2 sr
Temperature control	± 3 K
Pressure control*	± 10 Torr
Target element and isotope	$26 \leq Z \leq 82$, $56 \leq A \leq 132$
Incident ion energy	$100 \leq E \leq 500$ MeV/n
Charge and mass resolutions	$\sigma_Z \leq 0.1$ cu, $\sigma_A \leq 0.2$ amu
Observation period	100 days @ Antarctica balloon 3 years @ ISS

* Only by using CR-39

Table. 1. Characteristics of LHITA instrument: (upper panel) detector module size, (middle panel) instrument specification and (lower panel) observation details.

Module size	25 cm × 25 cm × 0.5 cm
Number of module	16 × 29 modules
Total size	4.0 m × 5.0 m × 0.005 m
Total Weight	400 kg +
Geometric factor	~ 16 m^2 sr
Temperature control	± 3 K
Pressure control*	± 10 Torr
Target element and isotope	$30 \leq Z \leq 92$, $Z < 92$,
Incident ion energy	$E \geq 3.0$ GeV/n
Charge resolution	$\sigma_Z \leq 0.2$ cu
Observation period	3 years @ ISS 100 days @ Southern hemisphere

* Only by using CR-39

Table. 2. Characteristics of LHAPS instrument: (upper panel) detector module size, (middle panel) instrument specification and (lower panel) observation details.

the hodoscopes at the top and bottom of instrument, which select only UH particles with the relativistic energy passed through the instrument and determine their trajectories by searching for their through-holes. The details of principle and methodology of particle identifications by SSTD as mentioned above is described in elsewhere [16,17].

IV. OBSERVATION PROGRAM

Since the flux of UH-GCRs is very low, the detector with a large collecting power is required to observe such UH events. Definitive measurements are almost available for International Space Station (ISS), long duration flight using super-pressure balloon over Antarctica or Southern hemisphere capable of carrying very large scientific payloads for a long extended period. In case of experiment onboard ISS, GCR telescope with extremely large exposure area of > 4 m^2 can be expanded for a long time as~ 3 years. The Japan Engineering Module (JEM) is attached to the ISS and has a large external space available for exposure experiments. For the experiments which require recovery, the Japan Aerospace Exploration Agency (JAXA) has been currently developing the H-II Transfer Vehicle (HTV) with docking and de-orbiting capabilities as well as a recovery capability [18,19]. We expect that this sample returning system will realize our experiment after the year 2011 at least. On the other hand, super-pressure balloon has some advantages of long duration flight for ~ a few month or more and relatively small variation of air thickness and a stability of high altitude without ballast. The super-pressure balloon is currently under development in JAXA [20]. We expect that our experiment by using super-pressure balloon will be realized a few years later. Whatever the case, we will challenge the observation of UH-GCR with the use of the most utilizable carrier.

The cut-off rigidities for the inclination of ISS, over the Antarctica and Southern hemisphere have been calculated to estimate the number of particles by assuming the energy spectrum of iron nuclei observed by HEAO-3/C2 [21]. The number of particles to be observed has been estimated for the case for 3-year of 4 m^2 detector area for ISS and in 100-day of 4 m^2 and 16m^2 over Antarctica and Southern hemisphere, respectively. The relative abundance of UH-GCRs is taken from HEAO-3/C3 [5] as references. The result based on the assumption for the number of particles expected for UH-GCRs is shown in Fig. 4.

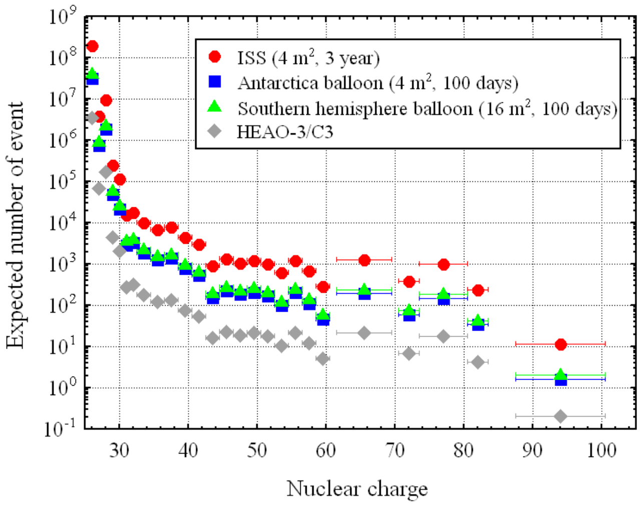

Fig. 4. Expected number of UH-GCR particle in three cases. Result obtained by HEAO-3-C3 is also shown.

V. Conclusion

The study of isotopic composition of ultraheavy galactic comics rays (UH-GCRs) is the next important step since the ACE/CRIS measurement of light isotopes (Z<30), because any data of isotopic abundances in the UH-GCR regions and also decisive data of elemental abundance in the region are not available. Isotopic abundance is less biased as for the chemical fractionation, which leads us to bring a preferred probe to study their origin. A large element and isotope spectrometer array made of solid-state track detectors (SSTDs) onboard International Space Station, a long-duration-super-pressure balloon over Antarctica and/or over Southern hemisphere will make the first measurement of the elemental and isotopic compositions of UH-GCRs with sufficient statistics for $Z \geq 30$ with the energy greater than 100 MeV/n.

Acknowledgment

This work was partially supported by the Grant-in-Aid for The 21st Century COE Program (*Physics of Self-Organization Systems*) at Waseda University from MEXT and by "Ground-based Research Program for Space Utilization" promoted by Japan Space Forum.

References

[1] J.C. Higdon, R.E. Lingenfelter, and R. Ramaty, "Cosmic ray acceleration from supernova ejecta in suberbubbles", *Astrophys. J. Lett.*, vol. 509, p. 33, 1998.
[2] R.E. Lingenfelter, J.C. Higdon, and R. Ramaty, "Cosmic ray acceleration in superbubbles and the composition of cosmic rays", *ACE 2000 Symposium, AIP Conf. Proc.*, vol. 528, p. 375, 2000.
[3] M.E. Wiedenbeck, W.R. Binns, E.R. Christian, A. C. Cummings, B.L. Dougherty, P.L. Hink, J. Klarmann, R.A. Leske, M. Lijowski, R.A. Mewaldt, E.C. Stone, M.R. Thayer, T.T. von Rosenvinge, and N.E. Yanasak, "Constraints on the Time Delay between Nucleosynthesis and Cosmic-Ray Acceleration from Observations of ^{59}Ni and ^{59}Co", *Astrophys. J. Lett.*, vol. 523, p. 61, 1999.
[4] P.H. Fowler, R.N.F. Walker, M.R.W. Masheder, R.T. Moses, A. Morley, and A.M. Gay, "Ariel 6 measurements of the fluxes of ultraheavy cosmic rays", *Astrophys. J.*, vol. 314, p. 739, 1987.
[5] W.R. Binns, T.L. Garrard, P.S. Gibner, M.H. Israel, M.P. Kertzman, J. Klarmann, B.J. Newport, E.C. Stone, and C.J. Waddington, "Abundances of ultraheavy elements in the cosmic radiation: results from HEAO 3", *Astrophys. J.*, vol. 346, p. 997, 1989.
[6] A.J. Westphal, P.B. Price, B.A. Weaver, and V.G. Afanasiev, "Evidence against stellar chromospheric origin of galactic cosmic rays", *Nature*, vol. 396, p. 50, 1998.
[7] S. Geier, B.F. Rauch, L.M. Barbier, W.R. Binns, J.R. Cummings, G.A. de Nolfo, M.H. Israel, J.T. Link, R.A. Mewaldt, J.W. Mitchell, S.M. Schindler, L.M. Scott, E.C. Stone, R.E. Streitmatter, and C.J. Waddington, "Observations of the Ultra-Heavy Galactic Cosmic-Ray Abundances ($30 \leq Z \leq 40$) with TIGER", *Proc. of the 29th Int. Cosmic Ray Conf.*, vol. 3, p. 93, 2005.
[8] M.H. Israel, W.R. Binns, A.C. Cummings, R.A. Leske, R.A. Mewaldt, E.C. Stone, T.T. von Rosenvinge, and M.E. Wiedenbeck, "Isotopic Composition of Cosmic Rays: Results from the Cosmic Ray Isotope Spectrometer on the ACE Spacecraft", *Nucl. Phys. A*, vol. 758, p. 201c, 2005.
[9] K. Sakurai, "A possible causal relation of the source composition of cosmic rays with the elemental depletion in the interstellar space", *Nucl. Phys. A*, vol. 718, p. 701c, 2003.
[10] N. Hasebe, M. Hareyama, S. Kodaira, and K. Sakurai, "Are Galactic Cosmic Rays Accelerated inside the Ejectae Expanding just after Supernova Explosions ?", *Nucl. Phys. A*, vol. 758, p. 292c, 2005.
[11] D.C. Ellison, L.O'C. Drury, and J.-P. Meyer, "Galactic Cosmic Rays from Supernova Remnants. II. Shock Acceleration of Gas and Dust", *Astrophys. J.*, vol. 487, p. 197, 1997.
[12] W.R. Binns, M.E. Wiedenbeck, M. Arnould, A.C. Cummings, J.S. George, S. Goriely, M.H. Israel, R.A. Leske, R.A. Mewaldt, G. Meynet, L.M. Scott, E.C. Stone, and T.T. von Rosenvinge, "Cosmic-Ray Neon, Wolf-Rayet Stars, and the Superbubble Origin of Galactic Cosmic Rays", *Astrophys. J.*, vol. 634, p. 351, 2005.
[13] J.C. Higdon, and R.E. Lingenfelter, "The Superbubble Origin of ^{22}Ne in Cosmic Rays", *Astrophys. J.*, vol. 590, p. 822, 2003.
[14] J.-P. Meyer, L.O'C. Drury, and D.C. Ellison, "Galactic Cosmic Rays from Supernova Remnants. I. A Cosmic-Ray Composition Controlled by Volatility and Mass-to-Charge Ratio", *Astrophys. J.*, vol. 487, p. 182, 1997.
[15] Y. Oganessian, "Sizing up the heavyweights", *Nature*, vol. 413, p. 122, 2001.
[16] S. Kodaira, N. Hasebe, T. Doke, A. Kitagawa, H. Kitamura, S. Sato, Y. Uchihori, N. Yasuda, K. Ogura and H. Tawara, "Mass resolution for iron-isotopes in CR-39 track detector", *Jpn. J. Appl. Phys.*, vol. 43, p. 6358, 2004.
[17] S. Kodaira, T. Doke, M. Hareyama, N. Hasebe, T. Miyachi, M. Miyajima, O. Okudaira, K. Sakurai, M. Takano, S. Torii, N. Yamashita, N. Yasuda, H. Tawara, S. Nakamura, K. Ogura, and H. Sshibuya, "High performance solid-state track detector for the observation of trans-iron isotopes in galactic cosmic rays", *Proc. of the 20th European Cosmic Ray Symp.*, (in this issue).
[18] T. Hiraiwa, , K. Fujii, A. Noda, and K. Yamanaka, "A concept Study of HVT Sample Return System", *IAC-05-B4.5-D2.7.04*, 2005.
[19] T. Imada, "Feasibility HTV operation requirement for sample returning capability from the ISS", *Acta Astronautica*, vol. 59, p. 392, 2006.
[20] N. Yajima, N. Izustu, and H. Honda, "Structure variations of pumpkin balloon", *Adv. Space Res.*, vol. 33, p. 1694, 2004.

[21] J.J. Engelmann, P. Ferrando, A. Soutoul, P. Goret, E. Juliusson, L. Koch-Miramond, N. Lund, P. Masse, B. Peters, N. Petrou, and I.L. Rasmussen, "Charge composition and energy spectra of cosmic-ray nuclei for elements from Be to Ni. Results from HEAO-3-C2", *Astron. Astrophys*., vol. 233, p. 96, 1990.