FINAL REPORT

The University of Alabama in Huntsville

PROGRAM: "Space Physics Supporting Research And Technology and Suborbital Programs"
Cosmic and Heliospheric Physics (C&HP)
F/NAS/NAGW-1651

TITLE OF INVESTIGATION:

"Development of Large Area Emulsion Chamber Methods with a super conducting Magnet for Observation of Cosmic Ray Nuclei from 1 GeV to 1,000 TeV" (Emulsion Techniques)

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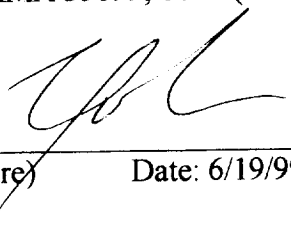

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CO-INVESTIGATORS:
Dr. John C. Gregory, Dr. Taka Tominaga, Ms. Bei Lei Dong

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1. Summary of the Research

The research at the University of Alabama in Huntsville was supported by the grant (NAGW-1651) for developing the fundamental techniques of the emulsion chamber methods that permit measurements of the composition and energy spectra of cosmic rays at energies ranging from 1 GeV/n to over 1,000 TeV/n. The research program consisted of exploring new principles and techniques in measuring very high energy cosmic nuclei with large-area emulsion chambers for high statistics experiments. These tasks have been accomplished and their use was essential in successful analysis of the balloon-borne emulsion chamber experiments up to 10^{14} eV. It also provided the fundamental technologies for designing large-area detectors that are aimed at measuring the composition at above 10^{15} eV region. The latter is now partially succeeded by a NASA Mission Concept, ACCESS (Advanced Cosmic Composition Experiments on the Space Station).

The cosmic ray group at the University of Alabama in Huntsville has been performed technological R & D as well as contributing the JACEE (Japanese-American-Emulsion-Chamber-Experiments) Collaboration with the regular data analysis. Other U.S. part of the JACEE collaboration were the Louisiana State University, NASA Marshall Space Flight Center and University of Washington. While primary research support for other institutions' efforts in the JACEE experiments came from NSF and DOE, primary support for the University of Alabama in Huntsville was the NAGW1651 program. Supplemental tasks to standardize the data base and hardware upgrades (automatized microscope) were jointly supported at three university groups by 1992 NASA Space Physics Research and Technology program NAGW-3540.

Investigation of new techniques in this program consists of fast calorimetry, magnetic/scattering selection of high momentum tracks for a pairmeter, and high statistics momentum measurements for low energy nuclei (E < 1 TeV/n). The highest energy calorimetry and a pairmeter have been considered as strawman instruments by the GOAL (Galactic Origin and Acceleration Limit) proposal of the NASA Cosmic Ray Working Group for long-duration balloon flights. We accomplished the part of the objectives of the GOAL with three circumpolar, Antarctic JACEE balloon flights during 1992 - 1994.

2. The Research Objectives Accomplished

The research program was devoted to (1) establish the cross section for direct electron-pair production, and in a designing study for its implementation in very high energy experiments. The cross section is now established to the degree we can rely on for application. A first-generation design was made in 1993 and a test pair-meter chamber was flown in the 1993-94 Antarctic circumpolar balloon flights (JACEE-12).
The emulsion chamber that (2) directly measures the rigidity of tracks of cosmic nuclei from 1 GeV/n to 1 TeV/n were also designed and waiting for a balloon flight with a superconducting magnet whose fabrication was completed in April, 1994. In this proposal we ask for a continuation of these work for the actual data analysis with high energy events from recent balloon flights. The work is further augmented by the finding of (3) the high energy cascade measurement method with a new and rapid data-taking scheme. It was discovered by this program and was named as "COREMETRY."

Several long-duration balloon flight exposures of the emulsion cambers were conducted by the Japanese-American-Cooperative-Emulsion-Chamber-Experiments (JACEE). The results from the program continues to develop the following techniques, and implement them in the actual balloon flight experiments and for future space experiments:

The new method, **(3)**, is the measurements of the size of the cascade core, which lets the highest energy cascade be measured fast. Its application is virtually unlimitedly to the very high energies exceeding 10^{16} eV, higher than the "knee" region energies. It is such a simple geometrical measurement that the coremetry is much faster than those of the previous techniques that used direct electron counting under a microscope or a micro-densitometry of electrons in x-ray films.

3.1. The Electron-Pair Method

We began the present research work with an introduction of the electron-pair method, which was based upon a uique and non-saturating relativistic rise. The high energy, high charge tracks of nuclei would copiously produce direct electron pairs along their tracks. These electron pairs are visible in emulsions very near to the nucleus track (within a field-of-view, < 100 μm). The number of pairs produced by a primary nucleus track (with charge Z) in 1 radiation length in emulsions is approximately,

$$N_{pair} \sim 100 \times (Z/26)^2 \times \log^2 (E/TeV). \qquad (1)$$

From this, the energy (Lorentz Factor) of a necleus track can be measured with a statistical errors of 15% for momentum. This direct electromagnetic method is not dependent on nuclear cascades, and the application above 1 TeV/n is not limited up to about 10^5 TeV/n (= 10^{17} eV/n). For this method to be applied in the actual balloon flight experiments, calibrations of the production cross section and the detection efficiency for pair observation were needed. The cross section was measured with emulsions and analyzed by using these 200 GeV/n sulphur beam at CERN SPS.

3. 2 Magnetic Rigidity Measurements with Super-JACEE

Further calibrations of electron-pair cross section and the detection efficiencies are needed at higher energies than 200 GeV/n. Known beam energy is required to utilize high energy cosmic ray nuclei for this purpose. The Super-JACEE experiment has been developed for momentum measurements of high energy cosmic nuclei up to about 2 TeV/n by using emulsion chambers in a 1.3 Tesla superconducting magnet.

Monte Carlo simulation incorporating multiple scattering, ionization loss and magnetic bend of a track has been performed for the beam telescope (20 cm in length) of emulsion chambers. The scanning window -size (w) is useful for automatically finding a track fast in the n-th layer of the emulsion plate at the position predicted by a curvature that is measured up to the (n-1)-th layer. The (w) value is found to be suitable at $w < 100$ μm so that the computer does not have to look at the entire data file of the auto-scanning. More than 97% of nuclei abobe 10 GeV/c/n will be found automatically by this set up and this detection efficincy is constant over the mmomentum range 10 - 1,000 GeV/c/n. The true momentum (p) and observed momentum (p') is compared to derive the resolution. The coordinate resolution (Δx) is 1.2 μm (from accelerator calibration experiments), for which the MDM is 5 TeV/c/n. This resolution is valid for ground experiements but it would be optimistic for cosmic ray applications in a balloon flight. The (Δx) is $\geq 2 - 3$ μm in the cosmic ray experiments and the MDM might be around 2 TeV/c/n.

3. 3 "Trigger" Method for High Energy Nuclei for A Pairmeter

Prior to scanning of electron-pairs in emulsions a pairmeter requires a "trigger" method to select high energy events among many low energy tracks of nuclei. The coordinates (x,y) of each nucleus track will be recorded in a harddisc in the automatic raster scan. A large stage microscope will make an all-area scan. Six CR-39 plastics scanned had the etch-pit holes diameter larger than 4 microns. Very high energy tracks that serve as fiducials for coordinates are already identified in a proto-type pairmeter chamber. These fiducial tracks have been obtained by the ordinary cascade measurements in the emulsion calorimeter section. Guided by the coordinates of the etch-pits for these tracks, three-dimensional corrections of the plate geometry (x_o, y_o, z_o) were performed, and each cosmic ray track were re-assigned with a corrected coordinate set (x', y', z'). This procedure has been repeatedly employed in the past in magnetic emulsion chambers for heavy ion experiments at CERN, and the reconstruction accuracy of track coordinates for each track over the entire chamber was established by us as ($\Delta x'$, $\Delta y'$, $\Delta z'$) = (1.2 μm, 1.5 μm, 2.2 μm). The Sagitta value (s) of multiple scattering is inversely proportional to the track momentum as shown below. It is 21 μm for a nucleus (A/Z = 2) at 300 GeV/n (= P/A) in a pairmeter with a height L = 20 cm and t = 2.4 radiation length.

$$s = (1/4\sqrt{3})\, L(\mu m) \times (13.6\ MeV/P\beta/A)\, Z \sqrt{(t/r.l.)} \times [1 + 0.20 \ln(t/r.l.)]. \qquad (2)$$

High energy events (E > 300 GeV/n) can be selected by the minimum value of Sagitta at the set value ($s <$ 4 μm). The emulsion data in CERN experiments was one of the best. In this case, we could set $\Delta x < 2$ μm and the maximum detectable momentum ($\Delta p/p \approx 100\%$) is 3.15 TeV/n.

4 Graduate Students

This program raised five graduate students (4 MS and 1 Ph.D). Kanaya Chevli, Scott Lynzenich, Joy Johnson, Toshiyuki Shiina (MS) and Mark Christl (Ph. D).

5. Publications (Journals)

"Cosmic-Ray Proton and Helium Spectra: Results from the JACEE Experiment," K. Asakimori, et al., Astrophysical Journal v.502, 278 (1998).

"Elemental Abundance of High Energy Cosmic Rays", Y. Takahashi, Nucl. Phys, **60B** 83 (1998)

"Laboratory Laser Acceleration and High Energy Astrophysics: γ-ray Bursts and Cosmic Rays," T. Tajima and Y. Takahashi, ApJ Supple. (in press), 1998.

"JACEE results on very high energy interactions," H. Wilczynski, et al., Nucl. Phys. B. , **52B,** 81 (1997).

"Search for Cosmic Strangelets with Supersonic Concorde and with the JACEE's Circumpolar Balloon Flight in Antarctica," Y. Takahashi, *Journal of Hyperfine Interactions*, Hyperfine Interactions, **103**, 99 (1996).

"Direct Production of Electron-Positron Pairs by 200-GeV/Nucleon Oxygen and Sulfur Ions in Nuclear Emulsion", J.H. Derrickson, et al., **Physical Review A**, 51(2), 1253-1259 (1995).

"A hybrid Set-up to study charmed particle production in ^{32}S - Nucleus Central Interactions," N. Armenise et al. (including J.C. Gregory, Y. Takahashi, T. Shiina), **Nucl. Instr. Methods in Physics Research, A361**, 497 - 505 (1995).

"Multi-Photon Decays of Heavy Particles," H. Wilczynski, et al., *Acta Physica Polonica B*, Vol. **26**, 861 - 872 (1995).

"Multiple-photon emission in heavy particle decays," K. Asakimori et al., (including J.C. Gregory, Y. Takahashi, T. Tominaga), JACEE Collaboration, **J. Phys. G. Nucl. Part. Phys. 20**, 1257-65 (1994).

"Transverse Momentum Distribution in 200 GeV/n S+Pb Interactions", A. Iyono, et al., **Nucl. Phys. A**, 544, 455-461 (1992).

II. Other Research Publications

"Results from JACEE Antarctic Balloon Flight," B. Nilsen, et al., proc. of the 97 Texas Symposium, Chicago, 1997.

"Scintillating Optical Fiber Calorimeter (SOFCAL) Instrument," M.J. Christl, W.F. Fountain, T.A. Parnell, F.E. Roberts, C. Benson, F.A. Berry, J.C. Gregory, and Y. Takahashi, SPIE 2806, 155 - 163 (1996).

"Cosmic Ray Proton and Helium Spectra – Results from JACEE," M. Cherry et al., Proc. 25-th Int. Cosmic Ray Conf, Durban, **4**, 1 – 4 (1997).

"Emulsion Chamber Experiments for the International Space Station," O. Miyamura, et al., Proc. 25-th Int. Cosmic Ray Conf, Durban, **5**, 17 – 20 (1997).

"Application of Pattern Recognition to Analysis of Emulsion Spectrometer," A. Iyono, T.A. Parnell, Y. Takahashi and T. Tashiro, Proc. 25-th International Cosmic Ray Conference, Durban, **7**, 289 – 292 (1997).

"Elemental Abundance at High Energies," Y. Takahashi and the JACEE Collaboration, **Edition Frontiers, Moriond Proceedings** 1996, Tranh Tanh Van (editor).

"Asymmetric Particle Emission in High Energy Cosmic Ray Interactions," H. Wilczynski, et al., *Proc. of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 1**, 1 - 4 (1995).

"Multi-particle Correlations in S + Pb and Pb + Pb Interactions at CERN SPS Energies," Y. Takahashi, et al *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 1**, 87 - 90 (1995).

"Search for Long Mean Free Path Nuclei with a Balloon-Borne Emulsion Chamber," O. Miyamura, et al., *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 1**, 890 - 893 (1995).

"Flux of Hyper-Strange Matter on Supersonic Concorde," J. N. Capdevielle, et al, *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 1**, 910 - 913 (1995).

"High Energy Gamma Rays above 3 TeV Observed by Balloon-Borne JACEE Emulsion Chambers," Y. Takahashi, K. et al., *Proceedings of the 24th International Cosmic Ray Conference, Rome*, Italy, **Vol. 2**, 451 - 454 (1995).

"Energy Spectra and Elemental Composition of Nuclei above 100 TeV from a Series of the JACEE Balloon Flights," K. Asakimori, et al., *Proceedings of the 24th International Cosmic Ray Conference, Rome*, Italy, **Vol. 2**, 707 - 710 (1995).

"Cosmic Ray Proton and Helium Spectra - Combined JACEE Results," M.L. Cherry, et al., *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 2**, 728 - 731 (1995).

"Results from an Antarctic Balloon Flight," E.D. Olson, K. Asakimori, et al., T *Proceedings of the 24th International Cosmic Ray Conference, Rome*, Italy, **Vol. 2**, 752 - 755 (1995).

"Antarctic Balloon Flights for JACEE," R.J. Wilkes, et al., *Proceedings of the 24th International Cosmic Ray Conference, Rome*, Italy, **Vol. 3**, 615 - 618 (1995).

"Direct Coulomb Electron Pairs for Energy Measurement- Design Consideration," J.H. Derrickson, et al., *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 3**, 641 - 644 (1995).

"Energy Estimate for Very High Energy Cascade by Core-Size Method in the JACEE Emulsion Chamber," M. Fuki and Y. Takahashi, *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, **Vol. 3**, 677 - 700 (1995).

"Results from JACEE and EMU05," Y. Takahashi and the JACEE Collaboration, **AIP Proc. 276, VIIth Int. Symp. on UHE Cosmic Ray Int.** (1993).

"Direct Electron Pairs Along Heavy Ion Tracks," J.H. Derrickson, Y. Takahashi et al., **Proc. 23rd Int. Cosmic Ray Conf.**, Vol. 2, p. 540 , Calgary, Canada, July 1993.

"Charged Particle Spectra and Isospin Clusters in S+Pb Interactions at 200 GeV/A," A. Iyono, Y. Takahashi et al.., **Proc. 23rd Int. Cosmic Ray Conf.**, Vol. 4, p. 13, Calgary, Canada, July 1993.

"Cosmic Ray Composition and Spectra (1) Protons," K. Asakimori, Y. Takahashi et al., **Proc. 23rd Int. Cosmic Ray Conf.**, Vol. 2, p. 21, Calgary, Canada, July 1993.

"Cosmic Ray Composition and Spectra (II), Helium and Z>2," Vol. 2, p. 25, K. Asakimori, Y. Takahashi et al., **Proc. 23rd Int. Cosmic Ray Conf.**, Calgary, Canada, July 1993.

"Multiple Photon Emission in Decays of Particles Produced in Cosmic Ray Interactions," H. Wilczynski, Y. Takahashi et al., Vol. 4, p. 29, **Proc. 23rd Int. Cosmic Ray Conf.**, Calgary, Jul 1993.

"Tickling the Knee with JACEE," K. Asakimori, Y. Takahashi et al., **Proc. 22nd Int. Cosmic Ray Conf.**, Calgary, Canada, July 1993, **4**, 708 (1993).