*This experiment was performed while the author was a staff member of the Plasma Physics Laboratory, Boeing Scientific Research Laboratories, Seattle, Wash.

[1] A. H. Mikesell *et al.*, J. Opt. Soc. Amer. 41, 689 (1951).

[2] V. I. Tatarski, *Wave Propagation in a Turbulent Medium* (McGraw-Hill, New York, 1961), Chap. 13.

[3] M. E. Tiuri, IEEE Trans. Antennas Propagat. 12, 930 (1969).

[4] G. J. Morris, Rev. Sci. Instrum. 39, 1156 (1968).

[5] G. J. Morris, Phys. Rev. Lett. 18, 734 (1967).

[6] R. A. Stern and P. K. Cheo, Phys. Rev. Lett. 23, 1426 (1969).

[7] A. Forrester *et al.*, Phys. Rev. 99, 1691 (1955).

[8] W. E. Drummond, Phys. Fluids 5, 1133 (1962).

[9] J. Weinstock, Phys. Fluids 10, 2065 (1967).

[10] R. A. Stern and N. Tzoar, Phys. Rev. Lett. 15, 485 (1965).

[11] D. T. Farley, J. Geophys. Res. 68, 6083 (1963).

[12] R. Hanbury Brown, Sky and Telescope 28, 64 (1964).

[13] R. Hanbury Brown *et al.*, Mon. Notic. Roy. Astron. Soc. 137, 375 (1967).

Evidence for a Primary Cosmic-Ray Particle with Energy 4×10^{21} eV

K. Suga, H. Sakuyama,* S. Kawaguchi, and T. Hara
Institute for Nuclear Study, University of Tokyo, Tanashi-shi, Tokyo, Japan

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We describe the analysis of an extremely energetic air shower produced by a primary cosmic-ray particle of energy 4×10^{21} eV. The arrival direction of this cosmic ray is right ascension 20 h 14.5 min and declination 24°. The directions of 3C409 (radio source) and AP2015+28 (pulsar) are inside the uncertainty of the arrival direction. Information on muons and the total number of charged particles in this air shower indicates no drastic change of nuclear interactions from 10^{17} to 10^{21} eV.

Analysis of an extremely large air shower (LAS) observed by the Institute for Nuclear Study, University of Tokyo (INS), air shower (AS) array and the INS LAS array at 17 h 55 min (JST) on 10 November 1970 indicates that the total number of charged particles (size) was 2×10^{12}. The energy of the primary particle which produced the air shower was 4×10^{21} eV. This energy is more than ten times higher than the energies of the largest showers reported previously.[1-4]

The INS LAS and AS arrays are shown in Fig. 1. The INS LAS array consists of four stations and the INS AS array is inside the INS LAS array and is separated by 300 m from station I. Each station of the INS LAS array consists of two unshielded 2-m^2 scintillation detectors separated by 50 m. Station IV was being constructed when the shower described in this paper was recorded. The INS AS array consists of 22 unshielded 1-m^2 scintillation detectors, a 20-m^2 spark chamber, four 2-m^2 scintillation detectors underground at a depth of 5 m ($E_\mu \geqslant 1.5$ GeV), four 2-m^2 scintillation detectors underground at a depth of 15 m ($E_\mu \geqslant 5.0$ GeV), and five $\frac{1}{4}$-m^2 fast-timing detectors. When the shower was recorded, ten $\frac{1}{4}$-m^2 scintillation detectors shielded with 1 cm of iron and thirteen $\frac{1}{4}$-m^2 scintillation detectors shielded with 1 cm of iron and 15 cm of lead were also being operated.

The arrival direction of the shower was determined by both the time differences of three stations of the INS LAS array and those of five $\frac{1}{4}$-m^2 fast timing detectors of the INS AS array. The arrival directions determined by both methods are consistent, and the zenith angle is 20° and the azimuthal angle is shown in Fig. 1. Uncer-

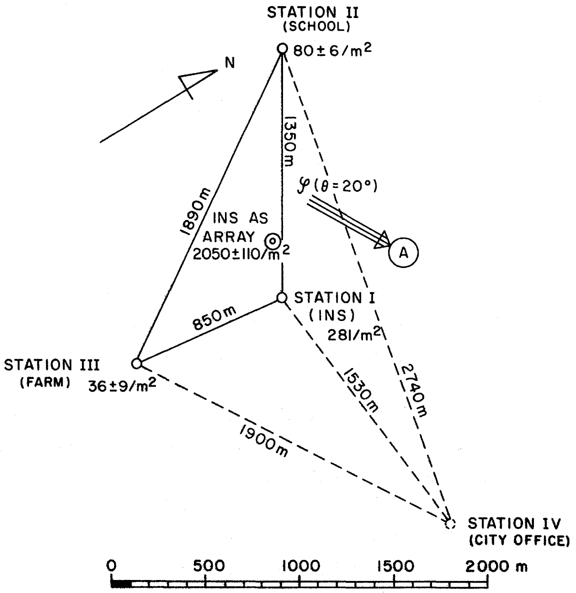

FIG. 1. INS LAS array with INS AS array inside, and the density pattern of the shower. The numbers near the stations and the INS AS array show the number of particles per m^2. A is the location of the shower axis.

tainty of the arrival direction of the shower is ± 4°. The right ascension and the declination of this arrival direction are $\alpha = 20$ h 14.5 min and $\delta = 24°$, respectively. The numbers near the stations and the INS AS array in Fig. 1 show the number of particles per square meter observed in the unshielded detectors. The characteristic feature of the density pattern over the INS AS array is that the densities in unshielded detectors are almost uniform over a circle of radius 50 m. The density measured by the spark chamber (Δ_{sp}) is 1135/m^2, and the density measured by scintillation detectors (Δ_{sc}) is 2050/m^2. After correction for the inefficiency of the spark chamber at high densities, we obtain 1.0 for Δ_{sc}/Δ_{sp}. This means that the size of the shower determined from the densities measured by scintillation detectors is the true size.

The density measured under 1 cm of iron is 1424/m^2, and the density measured under 1 cm of iron and 15 cm of lead is 457/m^2. The density of muons above 1.5 GeV is $(86.3 \pm 10.0)/\mathrm{m}^2$, and the density of muons above 5.0 GeV is $(27.4 \pm 5.5)/\mathrm{m}^2$. The integral energy spectrum of muons above 1.5 GeV thus measured is proportional to $E^{-1.0}$. The distance between the shower axis and the underground detectors is 690 m as described below. The energy spectrum at this distance is consistent with Greisen's formula for muons.[5]

Now we will locate the shower axis and determine the size of the shower. We can estimate the distance (r) between the axis and the INS AS array, assuming a form for the lateral distribution of charged particles and considering that the density pattern over the INS AS array is flat. r must be larger than 600 m for Nishimura-Kamata-Greisen (NKG) lateral distributions with $S = 1.4$ and $S = 1.0$, and r must be larger than 800 m for NKG lateral distribution with $S = 0.6$. Using Linsley's lateral distribution[6] where the characteristic scattering length and the zenith angle are adjusted for sea level, we determined the location of the shower axis as A is Fig. 1 and estimated the size to be $(2 \pm 1) \times 10^{12}$. The solid line in Fig. 2 shows the lateral distribution. The dotted line shows the lateral distribution of Linsley's largest shower[1] ($N = 5 \times 10^{10}$) after adjustment of the characteristic scattering length. This figure clearly shows that the size of the shower we observed is more than ten times larger than the size of the largest shower which Linsley reported. The lateral distribution of the shower is also fitted by an NKG function with $S = 0.8$, and the size of the shower is $(2\text{–}3) \times 10^{12}$.

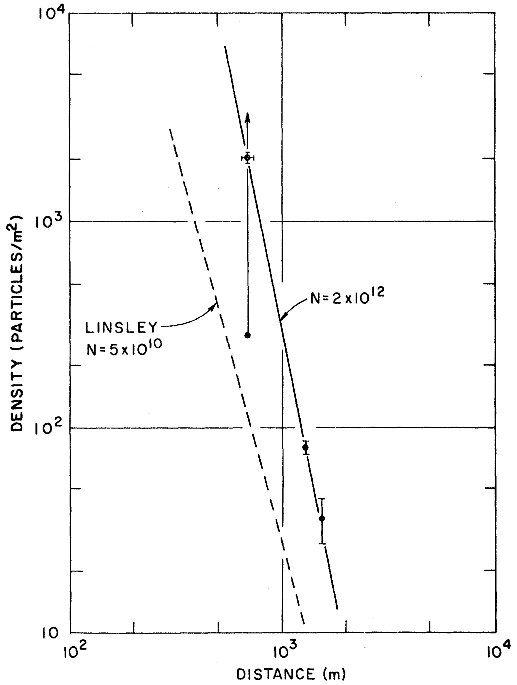

FIG. 2. Lateral distribution of the shower expressed as the densities (number per square meter) versus the distances from the shower axis. Solid line, present shower; dotted line, Linsley's largest shower ($N = 5 \times 10^{10}$).

In order to determine the size of the shower, we assumed that the lateral distribution is expressed by Linsley's lateral distribution or NKG functions even at smaller distances than 690 m which is the shortest distance from the axis for this shower. However, the real shower size depends very much on the lateral distribution from the axis to 690 m for which we do not have any information. Depending on the assumption about lateral distribution at these distances, the shower size is estimated to be 8×10^{11} for $S = 1.0$, and 3×10^{11} for $S = 1.2$. We have much information on the lateral distribution within several hundred meters from the axis for smaller showers. The lateral distribution whose S value is larger than 1.0 seems to be unreal for a shower as large as the present one. Therefore, the minimum estimate of the size is set as about half of the estimate mentioned before.

The estimation of the energy of the primary cosmic-ray particle is achieved both from the size of the shower and from the number of muons. At present, there is no analytical or Monte Carlo calculation on the relation between the primary energy and the size or the number of muons for energies above 10^{20} eV. Therefore, we extrapolate the calculations up to 10^{20} eV. As to the conversion of the size to the primary energy, the multiplicity law for the production of mesons is most important. Assumptions of inelasticity, interaction mean free path, and energy distribution of the produced mesons are treated as second-order effects, and these effects are included in the error for energy estimation under an assumption of multiplicity law. The energy estimates are as follows:

(1) $E^{1/4}$-law multiplicity,[7]

$$E_0 = (4^{+4}_{-2}) \times 10^{21} \text{ eV};$$

(2) $E^{1/2}$-law multiplicity,[8]

$$E_0 = (1.5 \pm 0.5) \times 10^{21} \text{ eV};$$

(3) $\ln E$-law multiplicity,[9]

$$E_0 = (6 \pm 3) \times 10^{21} \text{ eV}.$$

In the errors given above, the error from the uncertainty of the size is also included. The density of muons above 1.5 GeV at 690 m from the axis is converted to the total number of muons above 1.5 GeV by the lateral distribution of muons reported by the Sydney group,[10] $\rho_\mu \propto r^{-0.75}(1 + r/320)^{-(1.5 + 1.86 \cos\theta)}$. Comparing the number with the extrapolation of the calculation above 10^{20} eV, we obtain the primary energy from muons:

(1) $E^{1/4}$-law multiplicity,[7,11]

$$E_0 = 2 \times 10^{21} \text{ eV};$$

(2) $\ln E$-law multiplicity,[9]

$$E_0 = 8 \times 10^{21} \text{ eV}.$$

Although the estimated energy varies from 1×10^{21} eV to 9×10^{21} eV depending on the models, we take 4×10^{21} eV as a moderate estimate of the energy of the primary particle because the $E^{1/4}$ multiplicity law was mainly used for energy estimation of the largest showers. Then this shower is evidence for the most energetic primary cosmic-ray particle ever observed. Even if we take 1×10^{21} eV, the energy is still one order of magnitude higher than the highest energies reported already.

For the energy conversion at this extremely high energy, we have to check the processes which are not effective at lower energy. A competition between spontaneous decay of neutral pions and nuclear interactions in the atmosphere is not important even at the primary energy of 4×10^{21} eV. Landau-Pomeranchuk-Migdal[12] effects for pair creation by a high-energy gamma ray and for bremsstrahlung of a high-energy electron just begin to work for the $E^{1/4}$ multiplicity law at the primary energy of 4×10^{21} eV. Therefore, the energy estimate described before is not revised.

This extremely energetic shower is important not only for the energy but also for the fact that the shower provides information on electrons as well as on muons. Comparing the ratio of the number of muons to the size of this shower with extrapolations of calculations up to the order of 10^{21} eV, we conclude that there is no indication of a drastic change in nuclear interactions from 10^{17} to 10^{21} eV because the ratio is consistent with the extrapolations of calculations based on conventional models which explain the experimental results below 10^{17} eV.

It is worthwhile to mention that the directions of a pulsar, AP2015+28, and a radio source, 3C409, are inside the uncertainty of the arrival direction of shower. The distance between Earth and AP2015+28 is estimated to be several hundreds of parsecs. The direction of a cosmic ray with energy 4×10^{21} eV from an astronomical object at this distance is not affected by the galactic magnetic field. The distance between Earth and 3C409 is estimated to be 100 Mpc from the measured angular dimension[13] of 3C409 when the dimension is assumed to be a few times 10 kpc, the dimension of the identified extragalactic radio source. The intensity of the metagalactic magnetic field is estimated to be 2×10^{-9} G.[14] The radius of curvature of a cosmic-ray proton with energy 4×10^{21} eV in metagalactic space is therefore to equal or larger than 2×10^9 pc. Therefore, the deflection of a cosmic ray which may come from 3C409 to the earth is 3° or less. (The possibility that the particle has a charge exceeding 1 is excluded at this energy by the photodisintegration which would occur in a much shorter distance.) Thus, both AP2015+28 and 3C409 are candidates for objects which accelerated the cosmic ray. Although we cannot say anything definite on the origin of this very energetic cosmic ray at present, this stimulates us to further study on the importance of radio sources and pulsars as the origin of high-energy cosmic rays.

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[*] Present address: Department of Physics, Meisei University, Hino-shi, Tokyo, Japan.

[1] J. Linsley, Phys. Rev. Lett. 10, 146 (1963).

[2] D. Andrews, A. C. Evans, R. J. O. Reid, R. M. Tennent, A. A. Watson, and J. G. Wilson, Nature 219, 343 (1968).

[3] D. Andrews, A. C. Evans, R. J. O. Reid, R. M. Tennent, A. A. Watson, and J. G. Wilson, Acta Phys. 29, Suppl. 3, 343 (1970).

[4] R. G. Brownlee, G. J. Chapman, S. A. David, A. J. Fisher, L. Horton, L. Goorevich, P. C. Kohn, C. B. A. McCusker, A. Outhred, A. F. Parkinson, L. S. Peak, M. H. Rathgeber, M. J. Ryan, and M. M. Winn, Acta Phys. 29, Suppl. 3, 377 (1970).

[5] K. Greisen, Annu. Rev. Nucl. Sci. 10, 63 (1960).

[6] J. Linsley, in *Proceedings of the Eighth International Conference on Cosmic Rays, Jaipur, India, 1963,* edited by R. Daniels *et al.* (Commercial Printing Press, Ltd., Bombay, India, 1964), Vol. 4, p. 77.

[7] A. Ueda, Progr. Theor. Phys. 24, 1231 (1960).

[8] G. Tanahashi, private communication.

[9] C. B. A. McCusker, L. S. Peak, and M. H. Rathgeber, Acta Phys. 29, Suppl. 3, 527 (1970).

[10] M. M. Winn, in Summaries of the Second European Symposium on Cosmic Rays, Leeds, England, August 1970 (unpublished), p. 15.

[11] A. M. Hillas, J. D. Hollows, H. W. Hunter, and D. J. Marsden, Acta Phys. 29, Suppl. 3, 533 (1970); A. M. Hillas, in Summaries of the Second European Conference on Cosmic Rays, Leeds, England, August 1970 (unpublished), p. 22.

[12] K. Greisen, in *Proceedings of the Ninth International Conference on Cosmic Rays,* edited by A. C. Stickland (Institute of Physics and Physical Society, London, England, 1966), Vol. 2, p. 609.

[13] C. D. MacKay, Mon. Notic. Roy. Astron. Soc. 145, 31 (1969).

[14] K. Kawabata, M. Fujimoto, Y. Sofue, and M. Fukui, Publ. Astron. Soc. Jap. 21, 293 (1969), and to be published.

Thermonclear Origin of Rare Neutron-Rich Isotopes[*]

W. Michael Howard,[†] W. David Arnett,[‡] Donald D. Clayton, and Stanford E. Woosley
Rice University, Houston, Texas 77001, and Institute of Theoretical Astronomy, Cambridge, England

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Many rare neutron-rich isotopes in the range $16 \leq Z \lesssim 34$ can be synthesized from seed nuclei exposed to explosive carbon burning. This process, which involves no new astrophysical parameters, can solve most of the outstanding problems in the thermonuclear synthesis of elements in the range $Z \lesssim 34$.

For a theory of the origin of the atomic nuclei to be satisfactory, it must account quantitatively for the abundances of all of the stable nuclei, not just the more abundant ones. The explosive burning of oxygen and silicon nuclear fuel during rapid hydrodynamic ejection from stars produces the nuclei between silicon and nickel with convincing success[1] except for the relatively rare neutron-rich species ^{36}S, ^{40}Ar, ^{40}K, ^{43,46,48}Ca, ^{45}Sc, ^{47,50}Ti, ^{50}V, ^{54}Cr, ^{58}Fe, and ^{64}Ni. We are thus led to seek within the general picture of exploding stellar shells a naturally occurring circumstance for the synthesis of these nuclei from sources other than the primary fuels. We have discovered that a very promising site for this synthesis is in the shells that explosively burn carbon as a primary fuel, resulting in the primary products ^{20}Ne, ^{23}Na, ^{24,25,26}Mg, and ^{27}Al. During this nuclear combustion a brief but intense flux of neutrons and protons[2] converts already existing trace amounts (hereafter called *seed nuclei*) of the more common isotopes, primarily ^{32}S, ^{36}Ar, ^{40}Ca, and ^{56}Fe, into neutron-rich species with approximately the proper yield to account for many of the rare species. This process naturally accompanies the carbon combustion and thus requires no *ad hoc* hypotheses.

Quantitatively our calculations are based on the following reasoning. The previous theronuclear evolution of the star through hydrogen and helium burning has resulted in a stellar shell of ^{12}C and ^{16}O in roughly equal amounts. Heavier nuclear species, such as ^{40}Ca, exist at that time only by virtue of their inclusion in the original material of the star. For example, we expect ^{40}Ca to be present with the mass fraction $X_{\odot}(^{40}\mathrm{Ca}) = 8.11 \times 10^{-5}$ characterizing its natural abundance in the sun.[3] If this shell is now ejected in such a way that the explosive burning of carbon produces ^{20}Ne, ^{23}Na, and ^{24,25,26}Mg in their observed abun-