Fluorescence yields in determination of primary cosmic ray energy

Motohiko Nagano [1]

Abstract

The experiments on the search for the end of the cosmic ray energy spectrum are summarized. In estimation of the primary cosmic ray energy by the fluorescence technique, the determination of fluorescence yields in air is most important. If the preliminary yield at 337nm by AIRFLY measurement is used for Flys' Eye, HiRes and Auger, the differences of primary spectra among experiments are within experimental errors of each experiment, including suffface detector array experiment AGASA. In order to establish the energy scale, it is most important to determine the absolute fluorescence yield at 337 nm to understand the optical technique further.

1 Introduction

Cosmic rays are mainly protons and those in the highest observed energies may be the only samples of extra-galactic material directly detected. It has been of continuous interest to know from how far such samples are collected in relation to unknown physics at these energies as well as their exotic origin.

Figure 1 shows a compilation of cosmic ray spectra given by various groups over a very broad energy range. Only several results are plotted in the figure to highlight the main features of the spectrum. One of the mysteries of primary cosmic rays is that their energy spectrum extends over more than ten decades of energy almost continuously with only a few small changes in the slope in a power-law energy spectrum. It is hard to imagine any kind of astronomical accelerator which can cover such a broad energy range. Hence we need to find changes, if any, in their composition, arrival directions and slope of energy spectrum with energy to solve the mystery. The energies where the slope changes are observed are around 4×10^{15} eV (4 PeV), 6×10^{17} eV (0.6 EeV) and 4×10^{18} eV (4 EeV), which are popularly known as the *knee*, the *second knee* and the *ankle* respectively.

In my recent review [1], the experiments on the search for the end of the cosmic ray energy spectrum, with the particle detector array technique and the optical (Čerenkov and/or fluorescence) technique are summarized. The energy spectrum in the highest energy region is discussed in relation to that in the lower energy region. It is true, in principle, that the energy estimation by the fluorescence technique is most reliable since the primary energy is obtained experimentally by integrating the deposited energy in the atmosphere. Therefore the energy estimation does not depend on the hadronic interaction model or the primary species. However, there are several other factors in the determination of the energy experimentally in optical methods.

The important items related to the estimation of the deposited energy by the fluorescence technique are discussed in that review [1]. In this article, we focus only on the effect of fluorescence yields to the energy determination of the primary cosmic rays. The energy spectra normalized to the fluorescence yields at 337 nm determined by two experiments are compared with each other and the results will be discussed.

2 Observed energy spectrum in the highest energy region

The newly published energy spectra from the HiRes [2] and Auger [3, 4] experiments are compared with those published earlier (after 1990) in Figure 2, where the differential flux is multiplied by an energy dependent power E^3 to reduce the steepness of the power law spectrum. A prominent feature of the HiRes and Auger experiments is the suppression of the flux above the energy corresponding to the GZK cutoff with a statistical significance of 5.3 and 6 standard deviations respectively. The HiRes

[1]Department of Space Communication Engineering

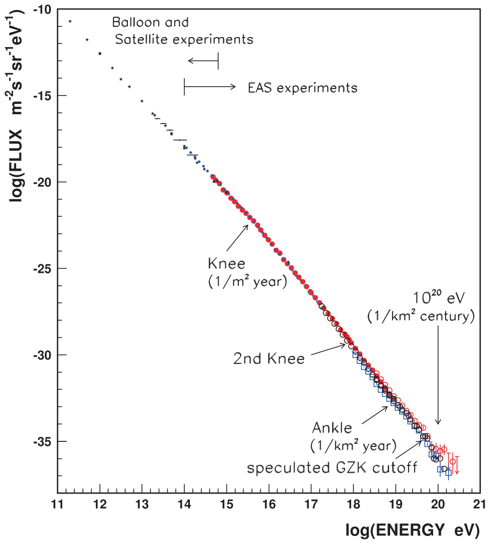

Figure 1: *Energy spectrum of primary cosmic rays. Akeno-AGASA results, which cover the widest energy range(*$10^{15} \sim 10^{20}$ eV*), are shown by red closed and open circles. Direct observations with balloon- and satellite-borne detectors are plotted as dots below the knee, around* 10^{15} eV*. New Tibet results which cover the energy region below and above the knee are plotted as blue circles. In the highest energy region, new results from HiRes and Auger are shown as open black circles and open blue squares respectively. The overall spectrum is expressed by a power law from* 10^{11} eV *to* 10^{20} eV *with only small changes of slope around* $10^{15.5}$ eV *(the knee),* $10^{17.8}$ eV *(the second knee) and* 10^{19} eV *(the ankle).*

energy spectrum is based on monocular data from HiRes-I and HiRes-II [2]. The Auger spectrum is the combined spectrum from 3 datasets, namely, vertical events observed by the surface detectors (SDs), inclined events observed by SDs and hybrid events detected by both the SDs and the fluorescence detectors (FDs). For every dataset the energy is calibrated using FDs.

The HiRes and the Auger experiments observe a flattening of the spectrum at an energy of 4.5×10^{18} eV and 4×10^{18} eV, respectively (*ankle*). It should be noted, however, that the *ankle* energy, E_{ankle}, is not determined accurately, either by HiRes-I or HiRes-II independently. Similarly, in the case of the Auger experiment, the *ankle* energy can not be derived for hybrid events or SD vertical events independently. They are determined by combining datasets from different measurements; in the case of HiRes, HiRes-I and HiRes-II, and in the case of Auger, hybrid events and SD vertical events.

In the same figure, Fly's Eye stereo spectrum [5] and HiRes stereo spectrum [6] are also plotted, which may be having better energy resolution than the monocular data. These spectra cover the E_{ankle} region with their own datasets. The ankle energy obtained from the Fly's Eye stereo data is 3.2×10^{18} eV [5] and that from the HiRes stereo data is estimated from the figure to be 5.6×10^{18} eV.

The AGASA spectrum [7] is plotted in the figure by reducing its energy by 10% based on the combined experiment with the Akeno array and the prototype AGASA array. This spectrum is in good agreement with the Akeno spectrum [8] in the overlapping energy region. The particle density at 600 m from the core, $S(600)$, has been used as an energy estimator by AGASA and the conversion to the primary energy is based on simulations [9, 10, 11]. The Akeno energy spectrum is based on the total number of shower particles N_e and the conversion to primary energy is based on experimental data on the longitudinal development curves measured at Chacaltaya and Akeno [12].

The HiRes-MIA spectrum is determined with a hybrid detector consisting of the HiRes prototype detector and the Michigan muon array (MIA) [13]. By using the hybrid timing information, the

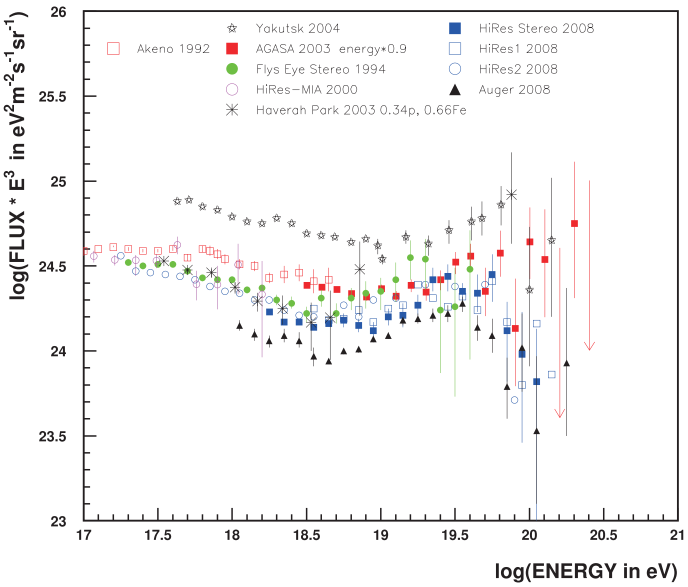

Figure 2: *Energy spectrum of primary cosmic rays from* 10^{17} eV *to* 10^{20} eV*. The differential flux in each bin is multiplied by an energy dependent power* E^3.

geometrical reconstruction is improved and hence the energy determination from the longitudinal development observed by the HiRes prototype is more accurate.

The Haverah Park spectrum is the re-analysed one using the QGSJET interaction model with the CORSIKA code [14]. In the figure, the case of mixed composition (34% protons and 66% iron nuclei) is plotted. A point at log E(eV)=19.9 represents four re-calculated events whose energies were estimated to be larger than 10^{20} eV in the original analysis [15]. The spectrum below $10^{18.6}$ eV is in good agreement with the Fly's Eye and HiRes results. However, the points around $10^{18.9}$ eV and $10^{19.9}$ eV are quite high (nearly in agreement with Yakutsk spectrum) and the results from the re-analysis between those energies have not been reported.

The Yakutsk spectrum reported in 2004 [16] is also plotted in Figure 2. The energy parameter, $S(600)$, the scintillator particle density at 600 m from the core, is calibrated experimentally with the calorimetric method by measuring the air Čerenkov radiation (70%∼80% of the total observed energy). By adding the energy carried by the electromagnetic component and the muons below the ground and the unobserved portion (8%), the relation between $S(600)$ and the primary energy is determined. The fluxes of the Yakutsk spectrum are quite high compared to the other results, however, they claimed the suppression of the spectrum above the E_{GZK} cut-off in 1991 [17].

3 Fluorescence yield

The fluorescence yield from the EAS particles was quantitatively studied and summarized by A.N. Bunner in his Ph.D thesis [18] and his results have been used for the Fly's Eye and HiRes analysis. The altitude dependence of the fluorescence yield and its energy loss dependence were examined by F. Kakimoto *et al.* [19] and their results have been used by the HiRes. Since the wavebands measured were limited only to 337, 381 and 391 nm in the studies of F. Kakimoto *et al.*, M. Nagano *et al.* [20] re-measured the fluorescence yield in 14 wavebands. The attenuation for each wavelength must be taken into account for the distant EAS, since the attenuation by Rayleigh scattering depends on the wavelength λ^{-4}.

Afterwards, the importance of more accurate measurements on the fluorescence yield for energy determination of EAS by fluorescence technique has been recognized and its dependence on pressure, temperature and humidity have been measured by several groups. Recent developments were reported at the 5th Fluorescence Workshop held at El Escorial in 2007 and their summary by F. Arqueros *et al.* [21] is found in the Proceedings of the Workshop.

In determining the primary energy with the fluorescence detector at Auger, the absolute fluorescence yield of the 337 nm band is taken from M. Nagano *et al.* [20] and the relative yields at other bands and their pressure dependence are taken from M. Ave *et al.* [22].

Table 1: *Comparison of the fluorescent efficiency in air.*

Wavelength (nm)	Experiment Beam Pressure	Bunner	Kakimoto *et al.* e (1.4 MeV) 800 hPa	Nagano *et al.* e (0.85 MeV) 800 hPa
		$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$
337		1.59	2.1	2.34
358		1.19	2.2	1.73
391		0.43	0.84	0.60

The fluorescence efficiency, defined as the radiated energy divided by the energy loss in the observed medium, summarized by A.N. Bunner [18] and measured by F. Kakimoto *et al.* [19] and M. Nagano *et al.* [20], is compared for three main wavebands in Table 1. It should be noted that A.N. Bunner estimated the values as a set of weighted average of three experiments, A.N. Bunner [23], G. Davidson and R. O'Neil [24] and P.L. Hartman [25]. These experiments used different methods with different operating conditions and an accuracy of each of these experiments is estimated to be not better than ±30% [18]. On the other hand, F. Kakimoto *et al.* and M. Nagano *et al.* studied β particles from the ^{90}Sr source penetrating the air and used fixed filters which accepted some contributions from the small side bands.

In order to compare the reported yields given in different units for different experimental conditions, F. Arqueros *et al.* [26] normalized them to photons per deposited energy at 293 K and 1013 hPa as listed in the last column in Table 2. Only some values relevant for the following discussion are shown here. Though a new AIRFLY result [27] is preliminary, its systemaic error is estimated to be less than 10%, which is smaller than those of F. Kakimoto *et al.*(> 10%) and M. Nagano *et al.* (13%).

Table 2: *Comparison of the fluorescence yield for 337 nm band in air. The last column is the yield normalized to 293 K and 1013 hPa per deposited energy calculated by F. Arqueros et al. [26] [28]*

Experiment	Experimental result			Yield/deposited energy at 293K, 1013hPa
	Temp.(K)	Pres.(hPa)	Yield	
Bunner			4.32 ph/MeV	
Kakimoto *et al.*	288	1013	1.1 ph/m	6.1 ph/MeV
Nagano *et al.*	293	1013	1.02 ph/m	5.5 ph/MeV
AIRFLY (preliminary)	291	993	4.12 ph/MeV	4.0 ph/MeV

Though there are significant differences in photon yield among the experiments, their exact differences on the energy determination are not simple to estimate. The contributions of all the lines passing through the filters used and the wavelength dependence of the attenuation of the number of photons must be taken into account in each event. Nevertheless, the following remarks should be made when comparing the experiments.

1. According to F. Arqueros *et al.* [26], the yield at 293 K and 1013 hPa for 337 nm band of M. Nagano *et al.* is estimated to be 5.5 photons/MeV for deposited energy taking into account the escape of delta ray from the field of view of the experiment. The Auger group uses the reported value of M. Nagano *et al.* whose fluorescence efficiency is determined under the assumption that the energy lost by the electron is fully deposited in the field of view. This value is about 10∼15% smaller than the value listed in the Table and hence about 5.0 photons/MeV [28]. Therefore the yield for 337 nm by M. Nagano *et al.* used by Auger is about 25% larger than that of preliminaly AIRFLY. If the preliminaly AIRFLY yield is confirmed, the estimate of primary energy for the Auger FD data based on M. Nagano *et al.* is likely to increase by about 25%.

2. Since F. Kakimoto *et al.* assumed that the energy lost by the electron was fully deposited in the field of view, 6.1 photons/MeV for deposited energy in Table 2 may be reduced to about 5.5 photons/MeV by similar discussion above. The HiRes group uses the absolute value not at 337 nm, but the integral value between 300 and 400 nm reported by F. Kakimoto *et al.*. This integral value could be converted to the yield per deposited energy at 293 K and 1013 hPa at 337 nm by F. Arqueros *et al.* and is 5.4 photons/MeV [26]. Therefore there is a question why the Fly's Eye spectrum based on A.N. Bunner and the HiRes one based on F. Kakimoto *et al.* nearly agree with each other in spite of using different absolute values at 337 nm (4.32 and 5.5 photons/MeV, respectively) and same relative values at other wave lengths.

3. According to B. Keilhauer *et al.* [29], the expected light from an EAS with a given energy deposit is reduced by 7% to 11% depending on the season, if the temperature-dependent collision cross-sections and water vapor quenching are used. This reduction value is obtained by applying to the measured atmosphere at Pierre Auger Observatory [30]. This means that the energy of the Auger energy spectrum must be increased by 7% to 11%. The effect of these temperature-dependent collision cross-sections must be taken into account for the Dugway atmosphere also, even though the effect due to water vapor quenching may be less at the HiRes and Fly's Eye site than at the Auger site.

Multiplication factors to the present energy of Fly's Eye, HiRes and Auger experiments are listed in Table 3, when the fluorescence yields at 337 nm is normalized to Nagano *et al.* or AIRFLY. Since the altitude dependence of humidity in seasons is not known for Dugway atmosphere, only upperlimit of the multiplication factors are shown for Fly's Eye and HiRes.

Table 3: *Normalization factor in each experiment, when the absolute fluorescence yield at 337 nm is normalized to Nagano et al or AIRFLY*

Experiment	Humidity	Nagano *et al.*		AIRFLY	
		Yield	Total	Yield	Total
Fly's Eye		0.86	>0.86	1.08	>1.08
HiRes		1.08	>1.08	1.35	>1.35
Auger	1.09	1.0	1.09	1.25	1.34

4 Normalized spectrum

Primary energy spectra normalized to the fluorescence yields at 337 nm to Nagano *et al.* (left) and to AIRFLY experiment (right) are compared in Figure 3. Factors listed in the column "Total" in Table 3 are multiplied to the energies of each fluorescence experiment as shown in the legend of figures. Surface detector array experiments of AGASA, Akeno and Haverah Park are also plotted. The Yakutsk results are excluded here, since the determination of single photon of Cherenkov light and the reason of the discrepancy of spectra of Yakutsk experiments between in the low energy region [31] and in the high energy region [16] has not been described in their reports.

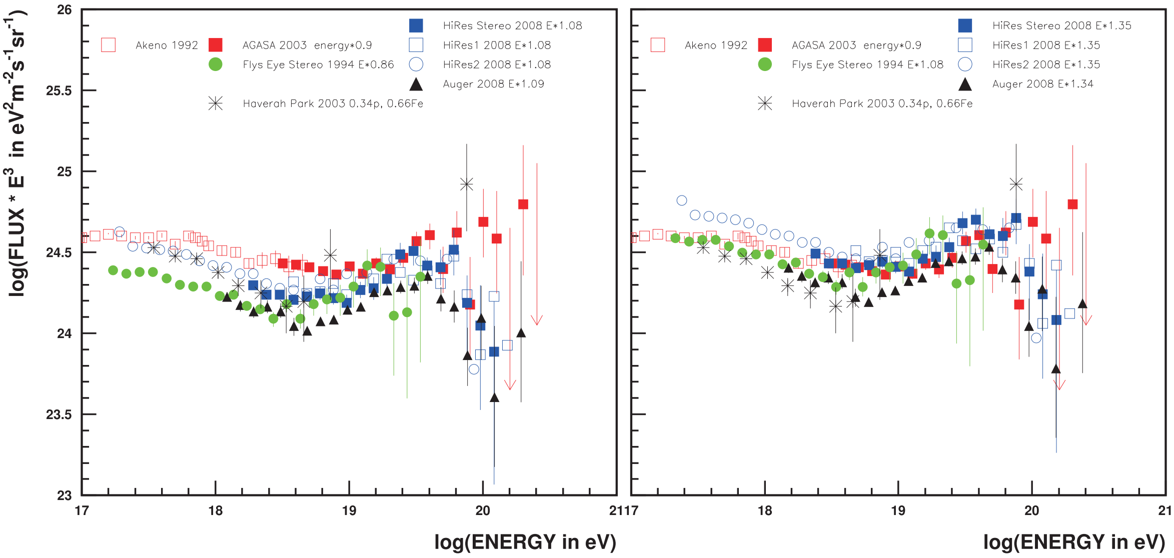

Figure 3: *Primary energy spectra from* 10^{17} eV *to* 10^{21} eV *normalized by a factor, which depends on the fluorescence yield at 337nm by Nagano et al. experiment (left) and that by AIRFLY (right) are compared.*

Agreements of energy among experiments are much better to AIRFLY normalization than to Nagano *et al.*. In the former case (right), the difference of fluxes among experiments are within statistical errors of each experiment. The statistical errors of fluxes above 10^{20} eV are large and hence the existence of super-GZK events may not be excluded.

In the latter case (left), differences among HiRes, Auger and Akeno remain, though they are reduced slightly.

5 Conclusion and outlook

Though the fluorescence technique measures, in principle, the total energy deposit in the atmosphere which is a good measure of energy, there are possibilities of accumulating errors at several stages. Some possibilities to increase the primary energy determined by the present fluorescence detectors are mentioned below.

- The energy of the Auger FD events must be increased by 7% to 11% depending on the season, if the temperature-dependent collision cross-sections and the actual humidity profiles at the site are used [29]. It is necessary to examine how much correction is necessary for the Fly's Eye and HiRes experiments for the Dugway atmosphere.

- The preliminaly result of AIRFLY experiment for the 337 nm band [27] is smaller by about 25%

than that of M. Nagano *et al.* presently used by Auger [21]. If AIRFLY result is confirmed, the Auger energy is likely to be increased by a similar amount.

Combining both of these amounts, there is a possibility of an increase of about 35% (10%+25%) for the Auger FD energy. In case of Fly's Eye and HiRes, the increases may be approximately 10% and 40%, respectively.

Further study on the determination of the absolute yield by the AIRFLY group is going on at GeV and MeV energies [27]. A confirmation of the absolute value for the 337 nm band is highly expected. Comparing to the novel but complicated procedure in absolute yield determination of AIRFLY, the photon counting method within a gated window by electrons is quite simple. Its systematic error is only limitted by the quantum and collection efficiencies of the PMT used. Their improvement is also highly expected.

The spectrum with the E_{GZK} cutoff is anticipated to recover beyond a few 10^{20} eV if the primary cosmic ray spectrum extends to energies far beyond 10^{21} eV [32]. To open a new window for charged particle astronomy covering the whole sky, the Auger North [33] and the JEM-EUSO projects [34] are under preparation. The JEM-EUSO [34] is expected to explore the anticipated recovery of the spectrum. Therefore our search for the end of the cosmic ray energy spectrum will be continued even after a century since the discovery of cosmic rays in 1912.

Acknowledgement

I gratefully acknowledge Naoto Sakaki and Fernando Arqueros for new information on fluorescence experiments. I wish to thank Suresh Tonwar for his valuable comments and suggestions.

References

[1] M. Nagano, NJP, (2009) to be publised.

[2] R.U. Abbasi *et al.*, Phys. Rev. Lett. **100** (2008) 101101.

[3] A.A. Watson, Highlight Talk at 30th ICRC, Mérida, México (2007).

[4] J. Abraham *et al.*, Phys. Rev. Lett. **101** (2008) 061101.

[5] D. Bird *et al.*, Astrophys. J. **424** (1994) 491.

[6] HiRes collaboration, to be published (2008).

[7] M. Takeda *et al.*, Astropart. Phys. **19** (2003) 447.

[8] M. Nagano *et al.*, J. Phy. G: Nucl. Phys. **18** (1992) 423.

[9] H.Y. Dai, K. Kasahara, Y.Matsubara, M. Nagano and M. Teshima, J. Phys. G. **14** (1988) 793.

[10] M. Nagano, D. Heck, K. Shinozaki, N. Inoue and J. Knapp, Astropart. Phys. **13** (2000) 277.

[11] N. Sakaki *et al.*, Proc. 27th ICRC, Hamburg **1** (2001) 329.

[12] M. Nagano *et al.*, J. Phy. G: Nucl. Phys. **10** (1984) 1295.

[13] T. Abu-Zayyad *et al.*, Astrophy. J., **557** (2001) 686.

[14] M. Ave *et al.*, Astropart. Phys., **19** (2003) 47.

[15] M.A. Lawrence, R.J.O. Reid and A.A. Watson, J. Phys. G. **17** (1991) 733.

[16] V.P. Egorova *et al.*, Nucl. Phys. B (Proc. Suppl.) **136C** (2004) 3.

[17] N.N. Efimov *et al.*, *Astrophysical Aspects of the Most Energetic Cosmic Rays* (ed. by M. Nagano and F. Takahara, World Scientific) (1991) 20.

[18] A.N. Bunner, Ph.D Thesis, Cornell University (1967).

[19] K. Kakimoto *et al.*, Nucl. Instr. and Meth. Phys. Res. A **372** (1996) 244.

[20] M. Nagano *et al.*, Astropart. Phys. **22** (2004) 235.

[21] F. Arqueros, J.R. Horandel and B. Keilhauer, Proc. of the 5th Fluorescence Workshop, El Escorial, Nucl. Instr. and Methods in Phys. Res. A **597** (2008) 1.

[22] M. Ave *et al.*, Astropart. Phys. **28** (2007) 41.

[23] A.N. Bunner, Thesis, Cornell University (1964).

[24] G. Davidson and R. O'Neil, J. Chem. Phys. **41** (1964) 3946.

[25] P. Hartman, Los Alamos report, (1963).

[26] F. Arqueros *et al.*, *arXiv:0807.4824v1 [astro-ph]* (2008).

[27] M. Ave *et al.*, Proc. of the 5th Fluorescence Workshop, El Escorial, Nucl. Instr. and Methods in Phys. Res. A **597** (2008) 55.

[28] F. Arqueros, *private communication* (2008).

[29] B. Keilhauer, J. Blümer, R. Engel and H.O. Klages, *astro-ph/0801.4200v2* (2008).

[30] B. Keilhauer *et al.*, Astropart. Phys. **15** (2006) 259.

[31] S. Knurenko *et al.*, Proc. 27th ICRC, Humburg **1** (2001) 145.

[32] P. Bhattacharjee, Proc. Int. Symp. on Extremely High Energy Cosmic Rays: Astrophysics and Future Observatories ed. by M. Nagano, ICRR, Univ. of Tokyo) (1996) 125.

[33] D. Nitz *et al.*, Proc. 30th ICRC, Mérida (2007) 180.

[34] T. Ebisuzaki *et al.*, Proc. 30th ICRC, Mérida (2007) 831.

(Received March 31.2009)