AN INSTRUMENT TO MEASURE ELEMENTAL ENERGY SPECTRA OF COSMIC RAY NUCLEI UP TO 10^{16} eV

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ABSTRACT

A longstanding goal of cosmic ray research is to measure the elemental energy spectra of cosmic rays up to and through the "knee" ($\approx 3\text{x}10^{15}$ eV). It is not currently feasible to achieve this goal with an ionisation calorimeter because the mass required to be deployed in Earth orbit is very large (at least 50 tonnes). An alternative method is presented. This is based on measuring the primary particle energy by determining the angular distribution of secondaries produced in a target layer using silicon microstrip detector technology. The proposed technique can be used over a wide range of energies (10^{11}–10^{16}eV) and gives an energy resolution of 60% or better. Based on this technique, a design for a new lightweight instrument with a large aperture (KLEM) is described.

EXISTING METHODS AND PROBLEMS IN HIGH ENERGY CR DIRECT MEASUREMENT

The quest for the origin of cosmic rays is one of the most fundamental problems of high energy astrophysics. The elemental cosmic ray (CR) energy spectra may contain features due to cosmological processes occurring in our Galaxy and possibly beyond it as well. Differences in the elemental energy spectra can also reflect the conditions of propagation and confinement in the Galaxy. The most valuable information can be obtained by direct measurements when a primary particle is detected because this allows the elemental identity to be determined. Such direct measurements must be made beyond the Earth's atmosphere.

In the energy range $E > 10^{15}$ eV, where practically all investigators observed a "knee" in the CR energy spectrum at $E \approx 3\times10^{15}$ eV, no direct observations have been done. Information on the CR spectrum in this region has been obtained by indirect measurements, first of all by the EAS technique. Direct measurement of CRs over a wide energy range up to and through the "knee" region are urgently required to clarify the situation.

The main difficulty in the direct study of high energy CR is the fact that throughout the abundant arsenal of modern experimental physics methods for energy measurement by a unified technique for all types of nuclei (Z=1-30) simultaneously (which is very important for determination of their intensity ratios) only the ionization calorimeter (IC) method may be applied over a wide energy range (over several orders of magnitude). But extension of the IC method to the high energy region ($E>10^{14}$ eV) would require the deployment of a very heavy (at least 50 tonnes) mass of flight qualified absorber beyond the atmosphere for a few years which would be extremely expensive. This is the main restraint on wide-scale investigations in the region concerned.

In parallel with the IC technique for the study of high energy CR so called kinematic methods could be used. They are based on detection of emission angles of secondaries produced in an inelastic interaction and carrying information about the energy of a primary particle. This technique does not require a thick absorber of released energy. A thin target (about 10 g/cm^2) is sufficient. Such methods traditionally have been applied with nuclear emulsions, which did not detect secondary gamma-quanta resulting from decays of neutral pions. Moreover the development of this technique to higher energy ($E>5\times10^{14}$ eV) is restricted because it is difficult to obtain a larger exposure factor due to the impossibility of prolonged (> 250 hours) exposure of nuclear emulsions.

A NEW APPROACH TO SPACE CR DIRECT ENERGY DETERMINATION

The essence of the proposed approach (Adams et al., 2000) is the application of kinematic methods in the investigation of high energy cosmic rays, using a gamma-quanta converter and silicon microstrip detector techniques for the measurement of emission angles of secondary particles. This approach allows several problems to be solved simultaneously:

(1) A decrease in the energy threshold of detection ($\sim 10^{11}$ eV/nucleon).
(2) The construction of a detector system with a relatively small weight but with a significantly large geometrical factor.
(3) The ability to make long-term exposures (1-3 years) in orbit and consequently provide the capability of conducting investigations in a wide energy range from 10^{11} eV/nucleon up to and beyond 10^{16} eV/nucleon with a unified technique.
(4) Inclusion into the analysis of information about emission angles of charged secondaries and also neutral secondaries with the help of a gamma-quanta converter.

A schematic illustration of the proposed method is given in Figure 1. A primary particle with energy E interacts in the target where secondary γ quanta and charged particles are produced. The γ-converter, a thin lead layer (11–22 g/cm^2) located at some distance from the target and just in front of the detector plane (DP), converts almost all secondary γ quanta to charged particles. The employment of advanced technology silicon microstrip detectors ensures the precision determination of primary particle charge and coordinates and secondary particle density. Charge resolution of about 0.1 charge units and spatial resolution of about 20 microns are expected. Advanced microstrip detector design and readout systems allow about 80% of the readout channels to be saved and significantly decrease power consumption and cost of electronics (Kotz et al., 1985; Krammer and Pernegger, 1997; Bashindzhagyan and Korotkova, 1999)

As a first gauge of the primary particle's energy an appropriate algorithm is:

$$S(E) = \sum \eta_i^2 , \qquad (1)$$

where the summation is conducted over all secondaries detected below the γ-converter, $\eta_i = -\ln \mathrm{tg}(\theta_i/2)$ is the so called pseudorapidity and θ_i is the secondary particle emission angle. On the one hand

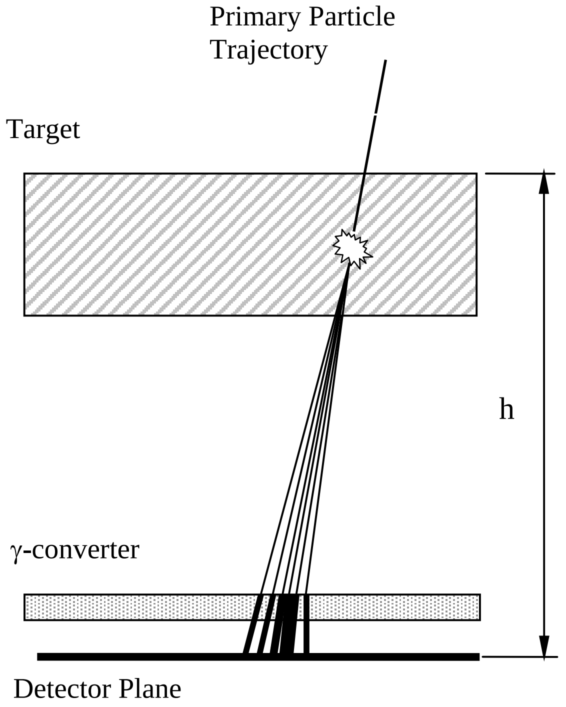

Fig. 1. Illustration of the proposd method.

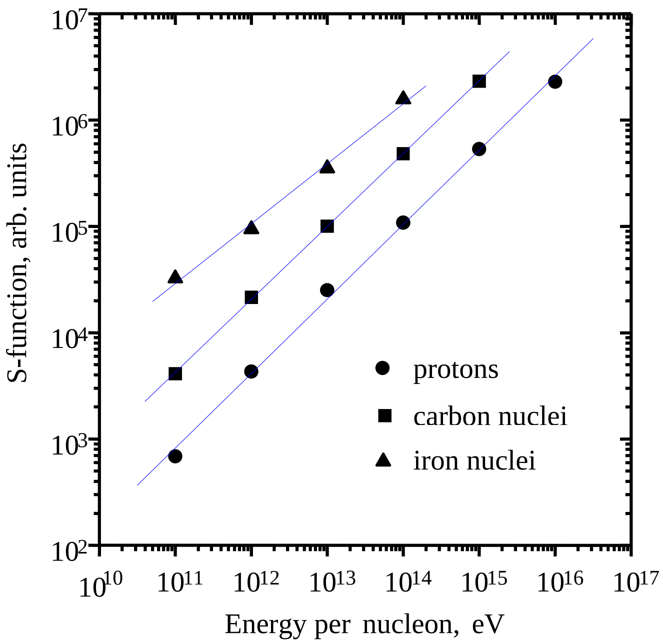

Fig. 2. Function S obtained from Eq. 1 as a result of simulation versus energy per nucleon for protons, carbon and iron nuclei.

function S characterizes the distribution of secondaries on emission angles being sensitive to the Lorenz-factor of the primary particle, and on the other hand S is proportional to the multiplicity of secondaries produced in the target and multiplied in the γ-converter. The combination of these two factors allows one to obtain for S a simple power law functional dependence on energy per nucleon for all types of primary nuclei over the entire range of energy.

The Monte-Carlo simulation was performed with the program complex GEANT 3.21, including different hadron-nucleus interactions codes: FLUKA, QGSM and QGSJET. The FLUKA generator was used for generation of hadron-hadron and hadron-nuclei interaction with E<50 GeV while QGSJET was used for hadron-hadron interactions with E>50 GeV. However, QGSJET "produced" only the masses of nuclear fragments, but not their transverse momentum. Simulation of transverse momentum was performed separately using results of emulsion CR experiments (Hayakawa, 1969). A data bank of more than 5000 events was generated for protons, carbon and iron nuclei in a wide energy range 10^{11}-10^{16} eV/nucleon. The simulation function S versus energy per nucleon is presented in Figure 2. For H, C and Fe nuclei S has very similar dependence on primary energy per nucleon $S \sim E^{\alpha}$, $\alpha \sim 0.8$. The steepness α of the S function on a logarithmic scale gets a little higher for a thicker γ-converter due to a larger number of secondaries.

The dependencies in Figure 2 were obtained under the assumption that the lateral resolution in detectors is absolute. Since microstrip detectors are used in detector plane (see Figure 1), the signals from secondaries hitting one strip will be integrated within the strip. In this connection the above suggested algorithm (Eq. 1) becomes:

$$S(E) = \sum \xi^2, \qquad (2)$$

where the summation is conducted over all strips; $\xi = -\ln \mathrm{tg}(\theta/2) \approx -\ln(0.5X/h)$. Here X is the coordinate of the strip center (X axis crosses strips perpendicularly). If the DP consists of two microstrip detector planes with strips going in perpendicular directions X and Y, one can obtain two practically independent measurements of the spatial distribution of secondaries and get an average value of E.

The relative error of protons' energy determination $\delta E/E = \delta S/(\alpha S)$ is shown in Figure 3 for two thicknesses of γ-converter (1 and 2 cm) and strip pitch 30 μm in the DP.

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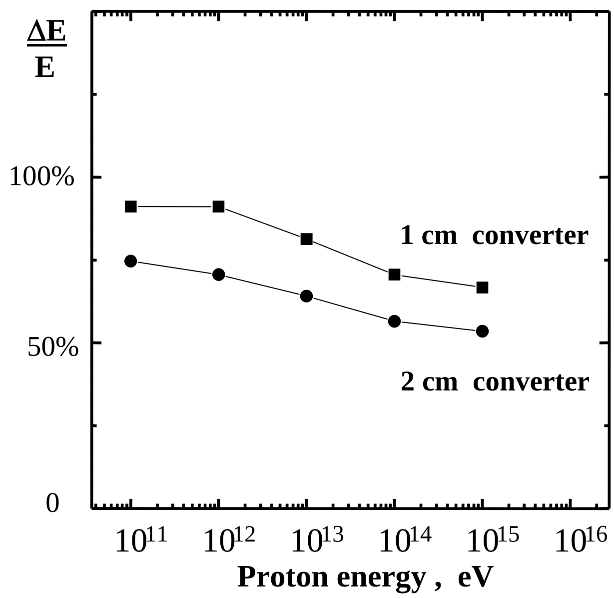

Fig. 3. Relative error of primary proton energy determination for two thicknesses of γ-converter.

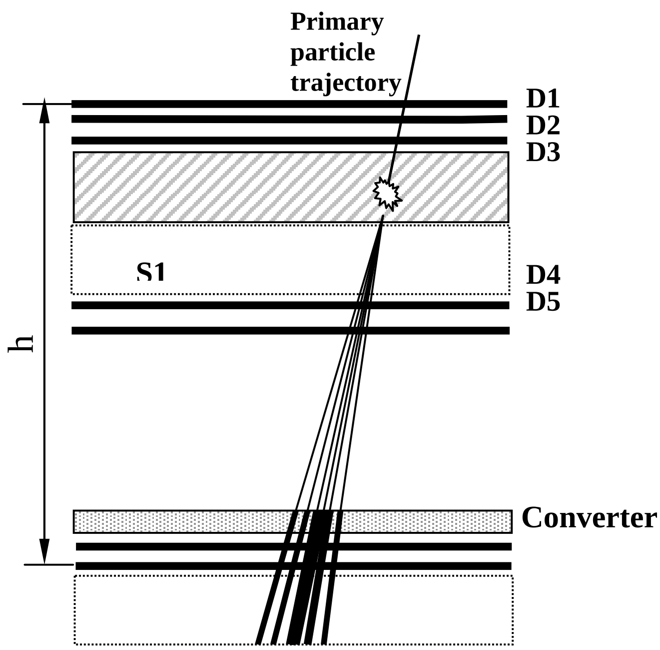

Fig. 4. Schematic layout of the KLEM–1B and KLEM–2 devices.

FOUR STAGES OF THE KLEM PROJECT

The proposed technique is being utilized to design and build a new advanced instrument for space CR experiments. The name of the suggested device is Kinematic Lightweight Energy Meter (KLEM). Based on preliminary results, a large scientific program of investigation, optimization and application of new approach has been proposed. Four stages are planned for the development of KLEM project.

Stage 1: KLEM–0

Development and optimization of the method and test of the new device at an accelerator. The stage is planned to be finished by the middle of 2001. During Stage 1 it is intended:

(a) to research and optimize the algorithm for primary particle energy determination

(b) to research and optimize the design of the device (target thickness, gap size, silicon detector strip pitch etc.)

(c) to develop a small prototype (KLEM–0). This will be based on a few silicon microstrip detectors of size 6×6 cm^2 each, with a carbon target and a lead γ-converter. The KLEM–0 device will be used for accelerator tests with proton/ion beams. It will have adjustable technical parameters (distances between the detecting planes, the target and γ-converter) and the possibility of being exposed at various angles.

Stage 2: KLEM–1A

Implementation of a CR experiment in the energy range 10^{10}-10^{13} eV with a balloon flight (KLEM-1A device). This will be a much larger but relatively simple instrument with approximate dimensions 0.40×0.40×0.35 m^3 and geometrical factor not less than 0.12 m^2 sr. The device is planned to be constructed in 2001 and exposed during a 6 to 7 day balloon flight in Siberia as was successfully carried out with the RUNJOB experiment. The completion of this stage of the project will be a major step towards effective high energy CR investigations by kinematic methods and would be a necessary stage of onboard testing and evaluation of the proposed technique.

Stage 3: KLEM–1B

Implementation of a CR experiment in the energy range 10^{10}-10^{14} eV with a satellite experiment (KLEM–1B device). The scientific objectives of the KLEM-1B experiment are:

(1) to study the absolute flux of protons and primary nuclei (He, C, O…) and the ratio of their power spectra in the range of energies $3\text{x}10^{10}$ - 10^{14} eV/particle

(2) to study the absolute flux and power spectra of secondary nuclei (Li, Be, B…) in the range of energies 3×10^{10}-10^{13} eV/particle.

Technical requirements and parameters proposed for KLEM–1B device are the following:

Approximate dimensions are 0.40x0.40x0.35 m^3.

Geometrical factor not less than 0.12 m^2 sr.

Expected energy range 3×10^{11}–5×10^{14} eV/particle.

Charge resolution less than one charge unit for nuclei with Z=1-30.

Accuracy of energy determination not worse than 60% in an individual case.

Total weight of equipment not more than 60 kg.

Power consumption not more than 95 W.

Exposure time not less than 1 year.

The proposed design of the KLEM–1B instrument is schematically shown in Figure 4. Seven layers (D1-D7) of silicon detectors with thickness of 300 μm, two layers (S1,S2) of plastic scintillator with thickness 0.5–1 cm, carbon target with thickness 10 cm and lead γ-converter with thickness 1–2 cm comprise the device structure. The layer D1 consists of a pad silicon detectors with the pad size about 2×2 cm^2 designed for precision measurement of primary particle charge with an achievable resolution 0.1 of a charge unit. D1 also provides identification of radiation scattered back from the target and converter. Silicon microstrip detectors in the D2 and D3 layers are set with perpendicular orientation, providing spatial resolution in the x and y coordinates of about 20 μm. They are designed to locate a primary particle trajectory, to identify accompanying shower particles in the case of interaction above the D1 layer, to help in backscatter particle recognition and to duplicate the D1 layer measurements. The D4 and D5 layers are similar to the D2, D3 layers and are designed for primary particle trajectory measurement. Similar layers D6 and D7 are designed mainly for the measurement of the spatial flux density of secondary particles originating in the target and multiplied in the converter. The expected separation of secondaries in D6, D7 layers is 30 μm. The detectors S1 and S2 are intended for prompt trigger elaboration, allowing the analysis of an event.

The efficiency of registration (W) in the proposed KLEM–1B device for different nuclei incident at average angles was calculated using the QGSJET model. The results obtained were: W > 32% for protons, W > 48% for He nuclei, W > 56% for C,N,O group nuclei and W > 84% for Fe nuclei at energies $>10^{14}$ eV/particle.

This project has been approved by the Russian Academy of Sciences and the Russian Space Corporation "Energia". The exposure for this stage is planed to be carried out on the Russian segment of the International Space Station or in a regular Russian satellite in 2003-2004.

Stage 4: KLEM–2

Direct CR experiments in the extremely wide energy range 10^{11}-10^{16} eV. The main scientific objective of this stage is investigation of "knee" problem in CR energy spectra at $\sim 3\times 10^{15}$ eV/particle. A large scale instrument (KLEM-2) is proposed as a major international space research experiment to be exposed in a dedicated Russian satellite in 2005-2007.

The proposed parameters of the KLEM–2 instrument are:

Total collecting area about 6–8 m^2.

Geometrical factor not less than 12 m^2 sr.

Expected energy range 10^{11}–10^{16} eV/particle.

Charge resolution less than one charge unit for nuclei with Z=1-30.

Accuracy of energy determination not worse than 60% in an individual case.

Total weight of equipment not more than 3000 kg.

Power consumption not more than 1000 W.

Exposure time not less than 3 years.

It is proposed to use the KLEM–2 device together with a regular calorimeter with much less collecting area. Such a combination allows one to have a cross calibrated system with a very high exposure factor. About 10-15% of primary particles cross both the KLEM–2 instrument and the calorimeter. Therefore KLEM energy measurements will be cross-checked by calorimeter determinations. On the other hand KLEM allows simultaneous measurement of primary particle charge and trajectory which is absolutely necessary anyway.

The efficiency of registration (W) in KLEM–2 for different nuclei at energies $E > 10^{15}$ eV/particle, calculated using QGSJET model, is: W > 42% for protons, W > 63% for He nuclei, W > 77% for nuclei of the C,N,O group and W > 95% for Fe nuclei.

It is assumed that CR spectrum intensity is 1.5–2.5 particles per $m^2 \times sr \times yr$ with $E > 10^{16}$ eV as has been determined in EAS experiments. Assuming that the duration of the exposure will be not less than three years and that the cosmic ray spectrum consists of protons only (minimum value of W) one can estimate the minimum expected statistical sample of events. This is found to be 25 particles with $E > 10^{16}$ eV. The acquisition of such statistics should allow useful direct measurements in the "knee" region. These measurements can be expected to shed light on the "knee" phenomenon and possibly determine the reason for the "knee".

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