Galactic cosmic rays from NUCLEON to HERO

(in Moscow State University)

D. Podorozhny for “Sources of Galactic cosmic rays”
APC, Paris - December 7-9, 2016
Ionization Calorimeter - main detector for high-energy particles

1957

N.L. Grigorov
I.D. Rapoport
V.S. Murzin
"Proton" Experiments
1965 – 1968

S.N. Vernov

Proton 4

N.L. Grigorov
The composition of cosmic rays experiment SOKOL

“Kosmos -1543” SOKOL-1
“Kosmos -1713” SOKOL-2
### Now in Russian Federal Space Program 2016-2025

#### 3 projects for Galactic cosmic rays exploring

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<tr>
<th>Project</th>
<th>Description</th>
<th>Stage 1</th>
<th>Stage 2</th>
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<td><strong>NUCLEON</strong></td>
<td>experimental study of cosmic ray spectra in energy range 1 TeV-1 PeV per particle with element charge resolution.</td>
<td>2007-2014</td>
<td>2015-2020 (+?) - Exposure stage</td>
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<td><strong>NUCLEON-2</strong></td>
<td>experimental study of Isotopic Composition: Z = 7-66 Charge composition: Z = 7-94 (+?) In the energy range E = 0.1-1.0 GeV / nucleon</td>
<td>2015-2020</td>
<td>2021-2026 (+?) - Exposure stage</td>
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<tr>
<td><strong>HERO</strong></td>
<td>(High-Energy Ray Observatory) - experimental study of high-energy astroparticle composition in energy range 1 TeV-10 PeV per particle</td>
<td>2017-2019</td>
<td>2025-2025 - Constructor stage</td>
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<td>Launch after 2025 before 2030</td>
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NUCLEON mission

NUCLEON apparatus is placed on board of the RESURS-P regular satellite as an additional payload. The spacecraft orbit is a Sun-synchronous one with inclination $97.276^\circ$ and an average altitude of 475 km. Lanched December 28, 2014. Switched on January 11, 2015. Flight test January-February 2015 From March 2015 up to now - regular measurements

The planned exposition time is more than 5 years.

**Vessel:**
- Weight ~360 kg
- Power consumption ~160 W
- Telemetry ~10 GB/day

The NUCLEON detector on board of the satellite RESURS-P N2.
The NUCLEON apparatus

- **system of charge measurements** – four planes of pad silicon detectors (1.5×1.5 cm²) (1);
- **tracker for KLEM energy measurement** – carbon target of 0.25 proton interaction lengths (2) and six planes of microstrip silicon detectors (0.4mm step) with tungsten between them (~2mm each, ~3 X-lengths summary) (3);
- **trigger sysytem** – tree double scintillator planes (4).

Active square 500×500 mm².
Geometrical factor 0.24m²sr.

- **Ionization calorimeter (IC)** (5) – six planes of tungsten absorber (~8mm each, ~12 X-lengths summary) with silicon strip detectors (1mm step).

Active square 250×250mm².
Geometrical factor (together with charge and KLEM systems) ~0.06m²sr.

10604 independent electronic channels in total
IMPORTANT FEATURE OF THE EXPERIMENT:

Two different methods of measuring of the energy of particles are implemented in the NUCLEON experiment:

1. The kinematic method **KLEM** (Kinematic Lightweight Energy Meter) -for the first time

2. The calorimetric method -usual and well studied
The kinematic method KLEM

The number of secondary particles with high pseudorapidity after the first interaction increases logarithmically along increasing of the primary energy of particle

The energies are reconstructed by S-parameter -

\[ S = \Sigma (l_i \ln^2(2H/x_i)) \]
KLEM energy resolution ~60% for all nuclei

calorimeter energy resolution ~50% for p
  ~30% for Fe
  ~8% for e

Correlation of the calorimeter energy deposit (Ed) and KLEM parameter (S) ~90%

This correlation is a model-independent result
Charge resolution of four silicon planes detector
~0.2 charge units
An example of an event «portrait»
Preliminary results\(^1\)

March 2015 - June 2016
\sim 1/5 expected statistics

\(^1\)The results are preliminary!
It is measured the all particles energy spectrum in the range of 3-1000 TeV by unified procedure.

There is an indication of the feature at 30 TeV (~2.8σ) "birdie" feature.
It is flating spectrum of helium compared with the spectrum of protons.

There is an indication that at energies above 100 TeV, the ratio of the slopes is reversed, but statistics is low.
Ne

\( \mathcal{L} \cdot E^{2.6} \cdot M^{-2} \cdot \text{cm}^{-2} \cdot \text{keV}^{-1} \cdot \text{cm}^{2} \cdot \text{sr}^{-1} \cdot \text{GeV}^{-1} \)

\( E, \text{GeV} \)

Mg

\( \mathcal{L} \cdot E^{2.6} \cdot M^{-2} \cdot \text{cm}^{-2} \cdot \text{keV}^{-1} \cdot \text{cm}^{2} \cdot \text{sr}^{-1} \cdot \text{GeV}^{-1} \)

\( E, \text{GeV} \)

Si

\( \mathcal{L} \cdot E^{2.6} \cdot M^{-2} \cdot \text{cm}^{-2} \cdot \text{keV}^{-1} \cdot \text{cm}^{2} \cdot \text{sr}^{-1} \cdot \text{GeV}^{-1} \)

\( E, \text{GeV} \)
Spectra of heavy nuclei (except iron) at energies above 500 GeV per nucleon is hard flat (spectral index ~ 2.4).

There is an indication that at energies of 5-10 TeV per nucleon this is a spectra break, but statistics is low.
The iron spectrum is steeper than the other spectra of heavy nuclei at energies above 100 GeV per nucleon (~ 4 $\sigma$).

According to the experiment data NUCLEON this effect exists up to energies of 2 TeV/n.
all particles spectrum “birdie” feature is stronger in (p+He+C) per particle spectrum ($\sim 3.2 \sigma$)

And it is loose in (p+He+C) per rigidity (nucleon) spectrum ($\sim 1.8 \sigma$)
Conclusions

• The preliminary analysis of the NUCLEON space experiment data gives multiple indications of the existence of a number of features in the energy spectra of cosmic ray nuclei at energies from few TeV to ~100 TeV (per particle).

• NUCLEON space experiment is continuing……
NUCLEON-2

The isotopic composition: $Z = 7-66$
Charge composition: $Z = 7-94$ (+?)
Energy range $E = 0.1-1.0$ GeV / nucleon
Basic requirements for NUCLEON-2 apparatus:
The geometrical factor should be at least $1.2 \text{ m}^2 \text{ sr}$;
Orbital lifetime apparatus should be at least $5 \text{ years}$;
NUCLEON-2 spectrometer measurements accuracy should be not less than $0.4\%$;
Energy area UHIS spectrometer should be $100-1000 \text{ MeV/nucleon}$

It is planned NUCLEON-2 apparatus will be placed on board of some regular satellite as an additional payload.
It is planned that the NUCLEON-2 will be consisting of separated towers.
Every HICRS tower (Heavy Isotopes Cosmic Rays Spectrometer) is independent for controlling

HICRS project design

- Two Si microstrip detectors, 100x100x0.3 mm, pitch ~1.5 mm
- Si pad detector, 100x100x2 mm,
- Power assembly design
- Read-out electronics area

HICRS has two symmetrical input windows
HICRS has «self trigger» system
Weight <3 kg
Power consumption ~3 W
544 independent electronic channels
NUCLEON-2 project design

Vessel:
- Weight ~ 220 kg
- Power consumption ~220 W
- Telemetry ~10 GB/day
- 27 000 independent electronic channels in total
Expected results for 5 years
(by estimation of HEAO-3-C3 and SuperTIGER data)

by simulation (GEANT-3, GEANT-4, FLUKA)
Neural network analysis
Multivariate statistical technique with maximum likelihood method

<table>
<thead>
<tr>
<th>Nucleus, Z</th>
<th>N</th>
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<th>N</th>
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<tr>
<td>Fe 26</td>
<td>3\times10^7</td>
<td>Ho, 67</td>
<td>24</td>
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<tr>
<td>Co 27</td>
<td>1.4\times10^6</td>
<td>Er, 68</td>
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<tr>
<td>Ni 28</td>
<td>1.1\times10^6</td>
<td>Tm, 69</td>
<td>29</td>
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<tr>
<td>Cu 29</td>
<td>1.6\times10^4</td>
<td>Yb, 70</td>
<td>110</td>
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<tr>
<td>Zn 30</td>
<td>1.6\times10^4</td>
<td>Lu, 71</td>
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<tr>
<td>Ga 31</td>
<td>2000</td>
<td>Hf, 72</td>
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<tr>
<td>Ge 32</td>
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<td>As 33</td>
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<td>Sr 38</td>
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<td>Au, 79</td>
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<tr>
<td>Dy 66</td>
<td>180</td>
<td>???</td>
<td>???</td>
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**HERO (High-Energy Ray Observatory)**

<table>
<thead>
<tr>
<th>&gt;E eV</th>
<th>$10^{14}$</th>
<th>$10^{15}$</th>
<th>$10^{16}$</th>
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<tr>
<td>N m$^2$sr year</td>
<td>2100</td>
<td>46</td>
<td>0.8</td>
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**General requirements:**

For solving $10^{14} - 10^{16}$ eV range problems it is necessary at least 100 m$^2$sr year exposure!

For peculiarities spectra - High energy resolution
- High charge resolution
- High rejection level: Protons/electrons+γ
- High rejection level: Gamma/electrons
**HERO pre-project design**

**Ionization calorimeter** consisting of 15 identical layers.
Each layer consists of a hexagonal plane, 25 mm thick and 2025 mm the diameter of the circle
Active medium in a layer - scintillator (\(\rho \approx 1.0 \text{ g/cm}^3\))
Absorber - tungsten-copper-nickel alloy (\(\rho \approx 16.0 \text{ g/cm}^3\)).

In each direction - 3 fiber
The light signal of each fiber are recorded PMT

**3060** - number of registration channels

**~10 tons** - Weight

**~40** - X-lengths

**~4 \(\lambda_p\)** - proton inelastic interaction length
IC is surrounded by a four layers silicon detectors (like NUCLEON) 
\(~2 \times 10^5\) - number of registration channels
HERO exposure – on Low Earth Orbit (weight saving)
Optimization in low Earth orbit - to orient the device by one of the six side surfaces to the Earth. (~ 50% increase in the geometric factor).
Total weight 12.5 tones
**HERO general characteristics**
(by simulation)

**Effective geometrical factor:** Protons ~ 9 m$^2$sr  
Nuclei ~ 14 m$^2$sr  
Electrons and gamma ~ 16 m$^2$sr

**Exposition factor:**  
Protons ~ 90 m$^2$sr year  
Nuclei ~ 140 m$^2$sr year  
Electrons and gamma ~ 160 m$^2$sr year

**Energy resolution:** Protons - ~ 20%  
Nuclei - ~ 10-15%  
Electrons and gamma ~ 5%.

**Charge resolution:** 0.2 charge unit.

**Rejection level:** Protons/electrons $10^5$-$10^6$  
Gamma/electrons $>10^3$