The INCA Project
I. Astrophysical Goals and the Concept of an Ionization-Neutron Calorimeter for Direct Investigation of Ultimate-Energy Electrons and Primary Cosmic-Ray Nuclei up to the "Knee" Region

The INCA Collaboration

Abstract

An experiment based on a so-called Ionization-Neutron Calorimeter (INCA) mounted aboard a satellite or a space station is proposed. The main goal of the experiment is to study local near-by sources of high-energy primary cosmic radiation (PCR) by recording (a) PCR nuclear component within the energy range 1 to 10 PeV; (b) PCR electron spectrum within the range 0.1 to 1 TeV. In addition, the experiment can provide new information on the cosmic γ-radiation in the unexplored energy interval 0.03 to 1 TeV, the neutral component of solar radiation, and very massive exotic charged particles.

1 Astrophysical goals of the experiment

The main goal of the proposed experiment is studying the local near-by sources of high-energy primary cosmic rays. According to recent speculations, the most promising way to do it consists in studying :

(1) The spectrum and composition of nuclear components of the PCRs in the energy range 0.1 to 10 PeV, i.e., in the so-called "knee" region (Erlykin and Wolfnendale, 1997) and

(2) the primary electron spectrum in the energy range 0.1 to 10 TeV (Shen, 1970).

Unfortunately, in both cases, available experimental data based on direct measurements are rather poor. While below the "knee" region, direct determinations of the PCR spectrum by means of high-altitude balloons in the upper atmosphere and aboard satellites were recently performed, PCRs with energies as large as and higher than the "knee" energy are detected up to now only by studying extensive air showers (EAS). Therefore, the PCR spectrum and composition are derived from the experimental data indirectly and often vary from one experiment to another. As a result, although the "knee" in the PCR spectrum was found about 40 years ago, its features, origin, and even existence are still being discussed, and this problem remains one of the central problems of the PCR physics.

Recent studies of PCR electrons with energies up to 2 TeV (Taira et al., 1993), indicate the existence of a near-by and relatively young sources of accelerated electrons (Nishimura et al., 1996; Chechin et al., 1997). However, there are no data at higher energies. The present situation is rather remarkable: Experiments have reached utmost energies beyond which no any known source can contribute significantly, and a sharp cutoff of the electron spectrum is expected. Thus, further extension of measurements beyond the energy region of 1 TeV and improvement of their accuracy could bring new, possibly dramatic, conclusions on acceleration and propagation of PCR electrons. However, these studies pose a great challenge to experimental PCR physics due to a noticeable background of high-energy protons, whose flux exceeds by the factor of about 10^3 that of high-energy electrons. Until now, no adequate technique has been developed for balloon and satellite experiments to solve the problem of a reliable suppression of this background.

Other important problems that could be solved on the basis of the method proposed below, are:

(3) studying cosmic γ-rays, in particular, generated by local sources or in γ-bursts within the energy range covered by neither balloon/satellite experiments nor EAS- array ones;

(4) detecting neutrons and γ-rays generated in solar flares; and

(5) searching for both relativistic and slow very massive exotic particles with anomalously low charge-to-mass ratio Z/A, which may contribute to Galactic Dark Matter.

The detailed discussion of the INCA's astrophysical goals is presented in (Alexandrov et al., 1998).

2 Basic principles of the INCA

All these problems could be solved on the basis of the proposed INCA experiment exploiting several novel experimental ideas:

(I) A concept of an ionization-neutron calorimeter (Alexandrov K.V. *et al.*, 1998, Proc.) for measuring particle energies, mass numbers, and separating PCR electrons and protons;

(II) A silicon detector on the basis of matrix bipolar structures (Murashov V.N., 1999) for measuring primary- particle charges, spatial coordinates, energy released in cascade showers, and particle's time of flight;

(III) An acoustic detector (as a possible option) for detection of massive exotic particles (Kotelnikov et al., 1998).

The INCA is a calorimeter of a new type proposed recently in the Lebedev Institute. The layout of the INCA is shown in Fig. 1. This calorimeter is based on well developed and widely used techniques of ionization calorimeters and neutron monitors. Such a combination makes it possible to determine particles' energies by two different and mutually independent methods according to both ionization and neutron signals and to separate primary particles of hadronic and electromagnetic nature. Indeed, a number of secondary neutrons evaporated by nuclei excited as a result of nuclear interactions of cascade particles in a heavy absorber is proportional to the primary energy. In addition, the neutron yield (at the same cascade energy) depends on the primary particle nature, being only 5 to 10% for electromagnetic cascades compared to hadronic ones. This yields an additional rejection factor for separation of electromagnetic and hadron cascades, so that the resulting (e, γ)/p rejection factor is by two or three orders of magnitude higher compared to other methods and can attain 10^6 to 10^7, the electron detection efficiency being not lower than 0.85 at energies from 0.1 to 100 TeV (Alexandrov K.V. et al., 1998).

It is important that the INCA's absorber is mainly a light substance (e.g., polyethylene) interlayered by thin plates of a heavy absorber. At a minimum weight, this provides the maximum geometry factor, the maximum absorber thickness in terms of nuclear-interaction lengths, and a reduced (according to the transition effect) effective radiation length for the development of electromagnetic cascades. These principles were tested experimentally in hadron and electron accelerator beams (Ammosov V.V. *et al.* 1998; Chubenko A.P. *et al.* 1998).

As Monte Carlo calculations (Alexandrov K.V. et al., 1998; INCA collaboration, 1999) show, for the absorber thickness of 200–300 g/cm^2, an expected accuracy of the energy determination attains 10–20% in the "knee" energy region. In addition, it was shown that, at the initial stage of the nucleus-initiated cascades (i.e., in a thin layer of about 50 g/cm^2 thick), the combination of neutron and ionization signals can be used to estimate the particle mass number A. The expected accuracy of the mass number determination at the energy of 1 PeV is 35% for protons and 15% for iron nuclei. This fact enables the separation between basic groups of nuclei (p, He, CNO, ..., Fe) to be realized and makes it possible to detect hypothetical particles with a very large mass. It is important that the neutron detection efficiency of about 20% can be attained in INCA versions being planned.

In the experiment proposed, the separation of electrons from γ -rays is provided by the particle's charge detector at a level of 10^3. The new concept of the charge detector exploits an idea of the local injection mechanism for the amplification by a bipolar-transistor structure of the weak ionization current produced by a charged particle penetrating the semiconductor, and the step-by- step transfer of non-basic current carriers along the transistor-cell chain (Murashov V.N., 1999).

The detector is a matrix structure containing a large number of cells (n-p-n transistors) deposited

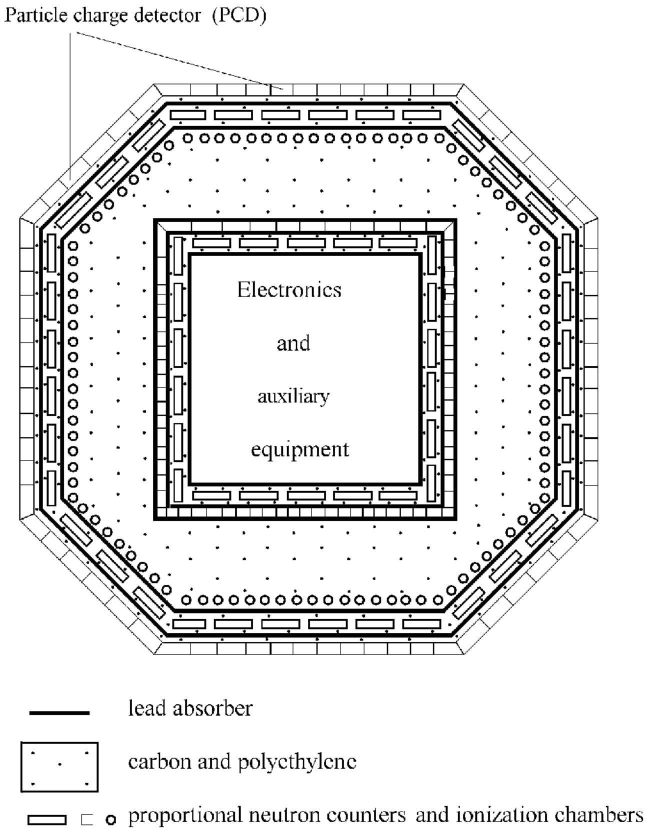

Figure 1: Cross section of the Ionization-Neutron CAlorimeter (INCA) with the Particle Charge Detector (PCD). Basic parameters are: weight = 4.6 - 9 t; $S\Omega = 10 - 30$ m^2·sr (up to 20 - 60 m^2·sr for iron nuclei); height = 1.5 m; diameter = 1.8 - 2 m; absorbers are carbon and polyethylene.

on the silicon base. The cell doubling principle is used in the matrix structure similar to the organization of a DNA molecule in leaving nature. This provides a high detector reliability and relatively low cost (compared to silicon strip detectors) as a consequence of a low failure factor when manufacturing. Preliminary studies show a feasibility of creating on the basis of such structures charge detectors with the following characteristics:

- sensitivity of about one tenth of the ionization charge produced by a single-chargedrelativistic particle;
- linear range of the measured ionization up to 10^5;
- time resolution better than 1 ns;
- spatial resolution better than 1 μm (the resolution required for the INCA is about 1 mm).
- high resistance to the ionizing radiation;
- temperature drift $< 1\%$ within the range -70 to + 70° C;
- high operation reliability (exceeding that for strip detectors by several orders of magnitude);
- low cost (1 to 2 USD per 1 cm^2).

Thus, this detector seems to be the most promising tool for measuring the primary-particle charge, particle coordinates, energy released in cascade showers, and time of flight.

To enhance the capability of detecting exotic particles, we propose to use, as a part of the INCA, acoustic sensors installed on structural INCA elements. This makes it possible to detect hypothetical massive low- velocity exotic particles that could compose Galactic Dark Matter and distinguish them against the background of heavy PCR nuclei and cosmic-dust particles (Kotelnikov et al., 1998).

3 Stages of the INCA project realization

We assume to realize the full-scale INCA Research Program in two or three stages.

The first one is aimed at development and testing in balloon flights of a 0.5-t prototype ("Mini-INCA"). Its high geometry factor and excellent electron/proton separation capability (the proton rejection of about 10^5) make it possible to measure the energy spectrum of primary cosmic-ray electrons in the energy region up to 1 TeV during a 10-day balloon flight under the conditions of strong suppression of the interfering proton background. This experiment will both testify the adequacy of the INCA concept for its realization in future satellite or Space Station experiments and verify previous data obtained by completely different (and sometimes not quite adequate) methods.

The final stage assumes construction of the full- scale 4 to 12-t INCA ("Maxi-INCA"). The Maxi-INCA requires a dedicated satellite. In this case, the expected statistics accumulated during (2-3)-year irradiation are: $N(E_0 > 1$ PeV$) = 2000$ to 6000 events and $N(E_0 > 10$ PeV$) = 40$ to 120 events (for nuclei); and $N(E_0 > 1$ TeV$) \geq 10^5$ events (for electrons). This statistic seems to be sufficient to solve the basic goals of the project. Such observations will hopefully allow us to clarify the most important sources or even to find hidden ones, to derive parameters of supernovae, such as epochs of explosion and relative strength of the power released and the explosion time and could provide us by the important information on the history of the local sources. On the other hand, these data can constrain the PCR confinement time, interstellar matter density and diffusion coefficient in the Galaxy.

As a possible intermediate stage, a "Midi-INCA" of 2-t mass could be constructed. This mass limitation makes the "knee" unattainable, while all other problems (including PCR spectrum and composition below 1 PeV) could be solved, the electron spectrum being the main goal. The Midi-INCA can be exposed both with large-size balloons and aboard a Space Station. In this case, the expected statistic for primary electrons is rather high even for high-altitude balloon flights and can reach 3000 to 5000 events in the energy range 0.1 to 1 TeV for 7-day flights.

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