G. B. Khristiansen. *Prospects for studying cosmic rays at ultrahigh energies (10^{15}–10^{21} eV).* It is common knowledge that cosmic rays yield new information important to space physics and astrophysics. It is also common knowledge that cosmic rays, discovered 75 years ago, played a major role in the origins and evolution of high energy physics in the 1930s, 1940s, and 1950s.

Cosmic rays are composed of protons, nuclei, muons, neutrinos and other particles with energies that greatly exceed those currently attainable at accelerators.

Table I lists data on the energies of protons, nuclei (with average atomic number A), and muons that have been or will soon be achieved in accelerator and cosmic ray experiments.

It is evident from Table I that the maximum energies of protons and nuclei in cosmic rays exceed those attainable at accelerators by several orders of magnitude now and for the forseeable future. Detectors suitable for cosmic rays of such enormous energies either already exist (the Yakutsk machine with effective detector area of 20 km^2) or will be constructed in the coming decade (the EAS-1000 machine with effective area of 10^3 km^2).[1]

In addition, Table I also shows that emulsion cameras make it possible to study interactions of various primary nuclei with various emulsion nuclei (from AgBr to Pb); the energy of cosmic nuclei in such processes markedly exceeds nuclear energies attainable at accelerators.

In accelerators colliding beam methods produced secondary particles of energy $E_{\max} < s^{1/2}$: the $s^{1/2}$ values attainable in this century constrain $E_{\max}$ to be lower than maximum cosmic ray energies by several orders of magnitude. In Table I muon data illustrate this result.

Research into muons and neutrinos at energies of 10^{14}–10^{15} eV is the primary goal of the DUMAND project, which in the USSR is carried out at an underwater facility at Lake Baikal.

Although research into cosmic ray interactions is beset with many practical difficulties (identification of interacting particles, low intensity of ultrahigh energy particles, and so on), the experience of the past decade (1970s–1980s) indicates that cosmic rays remain an evolving branch of high energy physics to this day. Many examples can be cited in support of this, for example: 1) the disproof of Feynman's hypothesis on the scaling nature of "weak" interactions at ultrahigh energies of 10^{14}–10^{15} eV[2] obtained at EAS facilities; 2) the first likely evidence of quark-gluon plasma formation in nucleus-nucleus interactions with incident nuclear energies exceeding 10^{14}–10^{15} eV (high average transverse momenta and very irregular rapidity distribution of secondary particles[3]).

All the same, the last decade has convincingly demonstrated the need for the closest collaboration between cosmic ray and accelerator research. Precision results, in many ways complete, that were obtained with accelerators proved

TABLE I.

Particle type	Accelerator		Particle type	Cosmic rays	
	Currently	1990s		Currently	1990s
p	1.38×10^6 GeV $s^{1/2} = 800$ GeV (USA)	1.8×10^7 GeV $s^{1/2} = 3\times10^3$ GeV (USSR) 8×10^8 GeV, $s = 2\times10^4$ GeV, (USA)	p and nuclei	10^{10} GeV at EAS (Yakutsk) facility and EAS AKENO (Japan) facility	10^6–10^8 GeV ANI (USSR) 10^{11}–10^{12} GeV EAS-1000 (USSR)
μ	280 GeV (CERN, Switzerland)	$<2\times10^4$ GeV	μ	2×10^4 GeV (MUTRON, Japan; REK, USSR)	10^5–10^6 GeV (DUMAND), "Baikal" facility (USSR)
Nuclei with average $A\approx30$	6000 GeV/particle (CERN, Switzerland)		Nuclei with $A\approx30$	10^5 GeV/particle (Japan–USA emulsion group)	

absolutely essential to the correct anaylsis of experimental cosmic ray data. The connection between accelerator (at 10^{12} eV energies) and cosmic ray data (at 10^{14}–10^{15} eV) turned out especially important in the disproof of Feynman's hypothesis. The need for either detailed weak interaction models or general principles based on accelerator data became obvious both in the analysis of hadron interactions in ultrahigh energy cosmic rays and in the field of cosmic ray astrophysics (for example, in the matter of determining the chemical composition of primary ultrahigh energy cosmic radiation). Thus, the ANI machine (in the town of Aragats, in the Armenian SSR, see Table I) dedicated to precision measurements of electronic, hadronic, and muonic high-energy components in EAS with primary energy 10^{15}–10^{17} eV should obviously make use of accelerator data at energies of the order of 10^{15} eV and the concrete models of weak interactions in order to confront the problem of extrapolating our understanding upwards in energy by two orders of magnitude.

One of the most pressing and, simultaneously, thorny problems in cosmic ray astrophysics is the question of the chemical composition of ultrahigh energy cosmic rays. The determination of the chemical composition is necessarily indirect and hence a quantitative solution becomes possible only after a single model of weak hadronic interactions is decided upon (at energies of 10^{15}–10^{17} eV at the ANI facility, for example, or at even higher energies at the EAS-1000 facility).

The energy spectrum and anisotropy of ultrahigh energy cosmic rays are practically independent of the particular interaction model dictated by accelerator data. The research techniques in the field (the "quasicalorimetric method")[4] are such as to require direct experimental data.

The energy spectrum of ultrahigh energy cosmic rays is plotted in Fig. 1. Although the existence of a "kink" at $3\cdot 10^{15}$ eV is beyond doubt and the general features of the spectrum up to 10^{19} eV have been measured, certain details (irregularities) in the spectrum and the total flux require further clarification. At energies exceeding 10^{19} eV the results of various authors differ both in form and in absolute magnitude.

Another characteristic of primary ultrahigh energy cosmic radiation that can be studied independently of interaction models is its anisotropy. In order to define this anisotropy one must measure the inclination of the EAS axis and its primary energy, as well as the solar time. Quantitative measurements of the amplitude and phase of the anisotropy will play a decisive role in resolving the question of spatial distribution of cosmic ray sources (galactic or metagalactic origin and so forth). Quantitative measurements of anisotropic fluxes from particular astrophysical objects (binary star systems, for example) should yield direct information on certain sources of ultrahigh energy cosmic rays.

To date some quantitative measurements of anisotropy have been carried out at energies of $2\cdot 10^{13}$ and $2\cdot 10^{17}$ eV only.[5,6] Data on ultrahigh energy cosmic rays from certain sources (Cygnus X-3 binary system with pulsar, Cygnus X-1 binary system with a black hole (Fig. 2)[7], and others) are only beginning to come in; the non-steady-state nature of these sources requires continuous observation.

Thus we find that cosmic ray astrophysics faces a number of concrete problems which require a qualitative improvement in the precision of measurements of individual EAS parameters and a qualitative improvement in the data acquisition rate. The aforementioned EAS-1000 facility,[1] which differs from other functioning EAS units not only in area (1000 km^2) but also in the qualitatively higher (by a factor of 30–50) density of shower particle detectors per unit area, is meant to address these immediate problems. This facility will permit: 1) precision measurements of the primary energy spectrum in the 10^{16}–10^{21} eV energy range; 2) quantitative measurements of cosmic ray anisotropy in the 10^{15}–10^{20} eV energy range; 3) quantitative studies of nuclear composition of primary cosmic radiation in the 10^{15}–10^{19} eV energy range. It will also permit constant observation of a number of ultrahigh energy cosmic ray sources in the Northern hemisphere (Cygnus X-3, Cygnus X-1, Hercules X-1 and others), as well as test the extrapolation possibilities of current weak hadronic interaction models to the ultrahigh 10^{18}–10^{20} eV energy range on the basis of EAS structural data.

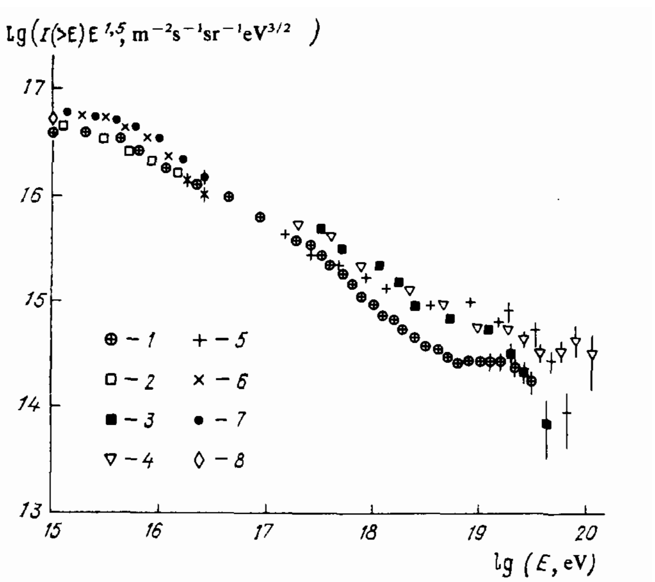

FIG. 1. Energy spectrum of ultrahigh energy cosmic rays: 1—Akeno, 2—Tien Shan, 3—Yakutsk, 4—Haverah Park, 5—Fly's Eye, 6—Samara State U., 7—Moscow State U., 8—"Proton".

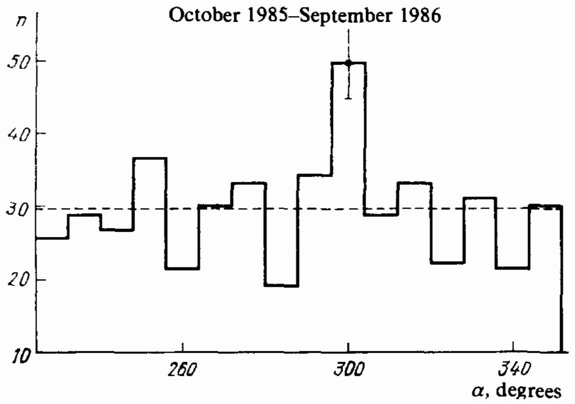

FIG. 2. Ultrahigh energy cosmic rays from Cygnus X-1.[7] Shower age > 1.3: peak excess is 21 showers on a background of 29 (3.8 σ).

In conclusion we note that prospects for research in the field of ultrahigh energy muons in cosmic rays are discussed in Ref. 8 and that there are currently no proposals for employing cosmic-ray nuclei with energies exceeding 10^{15}–10^{20} eV to study nucleus-nucleus interactions directly.

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