ORIGIN AND NATURE OF COSMIC RAYS

AND FIRST RESULTS FROM HEGRA

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Abstract: In part 1 a brief review of basic facts on the origin and the nature of cosmic rays is given for the energy range from 1 GeV to 10^{11} GeV. It is argued that our knowlegde on the most interesting questions on cosmic rays is very limited. Recently new experimental attempts are made to detect the photon component of the cosmic rays and to measure the chemical composition of the charged nucleonic part of cosmic rays. One such experiment is described in part 2 of this paper where the status of HEGRA is reviewed an air shower array at La Palma Canary Islands that aims for the detection of photons, protons and heavier nuclei in the energy range from 10^3GeV to 10^7GeV. First results on the performance of HEGRA and the searches for photons from point sources are given. The array will be apgraded in the near future as discussed at the end of this report.

Introductory remark.

The organizers of this meeting have asked me to give a short introduction to the field of cosmic ray experiments at very high energy. It was planned that this talk would be given by Jordan Goodman, Maryland who was however unable to come due to concerns with the safety of airtravel these days. I tried to do it on short notice. The material presented can be found in part I of this paper. Secondly ,in part II the status and future development of the airshower experiment HEGRA is given and some of the preliminary results on searches for point sources of cosmic rays.

I. 1 Energy spectrum and particle composition of primary cosmic rays.

The energy spectrum of cosmic ray particles considered here extends from the GeV region where the earth magnetic field and the local environment of the solar system have strong influence up to about 10^{11}GeV an energy high enough that the structure of our galaxy looses influence and the interaction of protons with the cosmological photon background is an important consideration.

The all particle energy spectrum follows a power law dN/dE $>E^{-\alpha}$, with α=2.7 up to ~ 10^6 GeV and α= 3.1 at higher energies. At the very end of the spectrum uncertainties are rather large due to small statistics and unknown systematics [1]. At the lower end of the energy range considered here the relative abundance of nuclei in cosmic rays is rather well determined and is found to follow, at least up to Fe, the so called solar system abundance with notable exceptions for Li, Be, B and F, Sc, Ti, V, Cr, Mn that are more abundant in cosmic rays by several orders of magnitude, about 10^5 and 10^2 respectively [2]. This is readily explained as due to spallation of heavier nuclei in interactions with the interstellar medium, mostly protons during the effective lifetime of charged cosmic ray particles within our galaxy [3]. At higher energies $> 10^4$ GeV/ nucleus, the relative abundance of nuclei heavier than carbon seems to become more important the data however from the JACEE experiment [4] has still rather small statistics. Above an energy of 10^6 GeV where the spectral index changes to a value α= 3.1 nothing is known about the charge of the primary cosmic ray particles.

Electrons (and positrons) as primary particles in cosmic rays have been detected up to 3 10^3 Gev, [5], and their spectrums falls off rather more steeply with α= 3.2 and a flux lower by a factor of 100 than the all particle flux at 10 GeV.

Primary photons have been detected by the satellite experiments SAS 2 [6] and COSB [7] up to energies of 5 GeV. The diffuse galactic flux seems to have a rather flat spectral shape with index α=2 in the outer galaxy and α=2.4 in the inner galaxy [8] at a flux level of 10^{-4} below the flux of charged particles at 1 GeV. In case this trend would continue to higher energies, photons would become more abundant than electrons at E $>10^{3-4}$ GeV.

Cosmic ray photons are most important for two of the basic questions of cosmic ray physics

1.) sites of C.R. acceleration
2.) distribution of C.R. in the galaxy

It would be of great interest to observe also primary neutrinos of cosmic rays however due to the very small reaction crossection of neutrinos with matter this is not feasible with present experimental techniques. Only very strong point like sources of neutrinos can be detected the most spectacular example (and so far the only one) has been the recent observation of supernova SN1987A, but for about 10 sec only at a neutrino energy of about 10 MeV.

I. 2. Galactic Sources of photons

Photons can be produced in electromagnetic interactions, including Bremsstrahlung of electrons on electrons and nuclei, inverse Compton scattering of high energy electrons on photons, where most of the electron energy is transfered to the target photon and synchrotron radiation of electrons in the ambient magnetic fields. All these processes require electrons to be accelerated to very high energies. Hadronic interactions are also a possible source of high energy photons, the dominant process is neutral pion production and decay to two photons, other possible processes like production of other unstable particles that decay to photons are known (from the systematics of hadronic interactions studied in great detail at accelerators) to be of much less importance. Alongside with neutral pions charged pions are produced that decay to neutrinos and muons which in turn decay to neutrinos and electrons thus creating a muon (anti) neutrino and electron (anti) neutrino flux in the ratio of 2:1 and of intensity similar to photons from neutral pion decay.

At any given environment matter is neutral overall and therefore, if ionised, both electrons and protons (nuclei) will be accelerated by whatever mechanism is at work. In general electrons will finally have much less energy however, since electromagnetic energy loss processes are rather efficient in reducing electron energies, at very high energy then proton acceleration with neutral pion production is expected to be the dominant source of photons. The protons hit the matter in the region nearby the acceleration site, or further out the protons of interstellar matter. Atomic hydrogen can be quantitatively traced through 21 cm line mapping of the galaxy while the density of molecular hydrogen can be determined using the assumption of proportionality to carbonmonoxid (CO). This rather general picture is quantitatively succesfull as applied to the COSB data on the diffuse galactic photon flux under the assumption of a cosmic ray particle flux everywhere in the galaxy similar to the flux observed near earth [9].

Both SAS 2 and COSB resolved a few (about 10) galactic sources compatible with pointlike origin and only two associated with known astronomical objects (Vela and Crab) [10]. At higher energies only the Crab nebula has been observed [11], other reports of observations, like from X-ray binaries (HerX1 or CygX3) lack sufficient significance to be accepted as photon detections.

I. 3. Extragalactic photons

Reports on the detection of extragalactic photons are very sparse, SAS 2 may have seen a diffuse flux at energies of 10^{-1} GeV, a claim that could not be substantiated by COSB due to higher background at a more unfavorable orbit. COSB concentrated on observations alongside the galactic disk but may have seen the quasar 3C273 at an observation at higher galactic latitudes[12)]. On this matter new information is expected soon, since the gamma ray observatory GRO has just been successfully launched.

The prospects of observing extragalactic photons at very high energies , much above the range accessible to GRO is however restricted to energies less than 10^5 GeV. Above this energy the absorption length of photons due to electron positron pair production on the ubiquitous 3^o K background photons is about 7 kpc [13)] comparable to galactic scales and much shorter than distances to extragalactic objects. On the other hand observing this cutoff on - say photons from M31 provides both a new method to determine astronomical distances and a proof that photons have been detected.

This same mechanism may be responsible for a cosmological photon flux at energies below 10^5 GeV originating from the proton cutoff due to photopionproduction at 10^{11} GeV. Assume protons have been accelerated to energies beyond 10^{11} GeV since galaxy formation in the early universe as a universal phenomenon. The energy lost to pions at $E > 10^{11}$ GeV is converted to photons and electrons that cascade down in energy through collisions with the 3^o K background until below 10^5 GeV, where the universe becomes transparent to photons. This photon flux has been estimated recently and may reach the level of $5\ 10^{-5}$ of the all particle flux[14)]. There is the possibility that this flux is virtually impossible to detect since it may be covered by the electron flux[5)] that is also isotropic and photons and electrons dedected as airshowers can not be distinguished at these energies. In any case only a rather narrow energy range from 10^4 - 10^5 GeV seems to be open for detection of this most interesting source of photons. The same mechanism may also enhance the photon flux from the direction of clusters of galaxies, like Virgo[15)].

II. HEGRA

An overview of the status and some preliminary results from the HEGRA experiment will be presented in this second part of my talk. HEGRA is an airshower array still under construction by a collaboration from Hamburg, Kiel, Madrid, Munich, Nottingham, Wuppertal and Yerevan at the Canarian island La Palma. Nevertheless, parts of the installation takes data continuously and results on the performance of the array and limits of photon fluxes from some of the prominent sources can be given.

II. 1. Goals of HEGRA

The array is designed to

a) find a photon signal from the well-established source of the Crab nebula

b) detect the diffuse flux of photons from the galactic disk

c) determine the mas distribution of charged primary cosmic rays

in the energy range from ~10^4 GeV to 10^7 GeV. Beyond those well defined aims the experiment should be capable to find more point like sources then just the Crab. In particular sources identified at energies of ~1 GeV by COSB (and future new sources to be detected by GRO) are an obvious target for HEGRA. As a more spectacular goal I would consider the discovery of a source visible only at energies > 10^4 GeV!

II. 2. Site and Experiment

The experiment is located at the astronomical site of the *observatorio del Roque de los Muchachos* at the Canarian island La Palma, at an elevation of 2200 m a.s.l. and usually well above the passat clouds that stay below 1800 m. The geographical coordinates are $18{,}1^o$ west and 28.8^o north. At present ~190 counter stations are installed on a regular 15 meter grid with in an area of 180 x 195 m^2. Each station consist of a scintillator 3 - 5 cm thick and ~$1m^2$, viewed from below by two PMT's to determine time and amplitude of particle signals from airshowers. All stations are covered with lead sheets of 1 r.l. thickness. This simple procedure considerably improves (~40%) the precision of the directional reconstruction of the airshowers on the basis of the arrival times at the counters. It is mainly due to photons converted to e^+e^- pairs, since photons form a more precise time front of the airshowers.

The array was started in summer 1988 with 37 counters from the Kiel group[16)] and later extended by the groups from Munich and Madrid to the present size. The array is triggered on a very simple multiplicity requirement, e.g. 7 or more stations fired in the whole array at a rate of a few Hz. All information on showers is logged via a MAC SE to a worm optical disk. Offline analysis is presently performed in Munich. About 80 Million triggers have been recorded. Well over 99% are due to airshowers with an energy threshold at about $5 \cdot 10^4$ GeV. The acceptance for airshowers in terms of celestial coordinates is almost uniform in RA (the plane of the array is slightly inclined with horizontal) and a gaussian in declination centered a 29^o and with a FWHM of 53^o. The shower front for most of the data is found to be of conical shape with a slope of ~14 nsec/100 m. The angular resolution is < 1^o for most of the showers and improves with shower energy (number of stations) to about 0.3^o at the higer energy end.

The absolut pointing of the array as well as the angular resolution was checked by searches for the shadow of moon and sun that both should completely absorb particles incident from their direction. We find as a preliminary result a reduction in flux due to moon and sun an absorption of about 20% at a significance level > 3.5 σ. This is well consistant with our Monte

Carlo estimates of the angular resolution and constitutes a proof of a much improved performance of HEGRA over previous arrays.

II. 3. Results

The results reported here are preliminary in nature to the extend that our full data set in conjunction with a more refined analysis will certainly result in considerable improvements. A search was made for an excess flux of airshowers from preselected locations in the sky. The procedure is simply to compare the number of showers in a bin size of $3^o \times 3^o$ centered at the possible source with the predicted number of showers from the bins shifted in RA but at the same declination. No excess has been observed. The data cover the range from 5.8.89 till 13.8.90; $2.2 \cdot 10^7$ event are used, for an effective lifetime of 218 days. Limits for fluxes are given at 90% c.l. at an estimated energy threshold of $7 \cdot 10^4$ GeV and for an effective detection area of 13000 m^2 (table 1).

Table 1: Flux limits of a steady excess of airshowers from some possible sources that were claimed to show excess fluxes in some earlier reports.

Object	Flux Limit (cm^{-2} sec^{-1})
Cygnus X3	$3.8 \cdot 10^{-13}$
Cygnus X1	$3.6 \cdot 10^{-13}$
Her X1	$5.0 \cdot 10^{-13}$
Crab	$4.3 \cdot 10^{-13}$
PSR 1937+21	$5.3 \cdot 10^{-13}$
PSR 1953+29	$5.4 \cdot 10^{-13}$
M31	$4.3 \cdot 10^{-13}$
Geminga	$5.8 \cdot 10^{-13}$

For the much discussed source Cyg X3 the present flux limits are more than an order of magnitude below earlier observations, either Cyg X3 has been dormant in 1989 - 1990 or the reported fluxes where just fluctuations whose significance was overinterpreted. For the Crab the present sensitivity is not good eneough to reach the flux levels at E > 10^4 GeV predicted on the basis of extrapolations from the Whipple results at 10^3 GeV. No attempt was yet made to see an excess of flux from the galactic disk, the statistics of our data however is not sufficient by at least an order of magnitude to have a real chance to see a photon flux at the level of 10^{-3} of the cosmic ray flux.

II. 4. Extensions of the HEGRA

We plan to install more detectors inside the limits of the present array (~200 x 200 m^2) in the very near future. The aim is an identification of the nature of the primary particle, in particular photons and heavier nuclei on the basic of muon detection..

II. 5 Lower threshold

We consider it of great importance to lower the trigger threshold of HEGRA at least for part of the area. Therefore 50 stations will be added to the array in the central part covering about 10^4 m^2 effective area. This primarily improves the angular resolution of lower energy showers. The trigger threshold could have been lowered already now by requiring ≥ 4 stations, however the determination of shower directions would be to poor. A lower threshold will also increase the trigger rate and therefore the statistics of our data samples by about an order of magnitude. This can no longer be handled with the present online system. A new setup will therefore consist of Fastbus moduls with an online computer based on a risk processor. We hope to finish this part of the HEGRA extension this year.

II. 6. Muon counting

Muons will be identified in a 6 layer sandwich type structure based on lead sheets as absorbers and 6 meter long Geigertubes to track muons. The Geigercounters are taken from the FREJUS proton decay experiment that finished running Sep. '88. A total area of about 600 m^2 will be covered this way and the muon energy threshold is at about 0.5 GeV.

II. 7. Cerenkov light detection

We are going to build two rather different sets of detectors to record the Cerenkov light emitted by (mostly) the electrons in the airshowers. Firstly an array of 7 x 7 = 49 PMT's with 30 m grid spacing will be installed inside the HEGRA area. Each stations will have one PM hemispherical in shape with 20 cm in diameter to collect the night sky light through a conical mirror with a half angle acceptance of 35^o. The PM's have only seven stages followed by a fast amplifier to register the extremely fast (few nsec) Cerenkov light pulse from airshowers on top of a rather high, but very uniform star light background. Tests carried out recently with specially designed PM's are very promising. We expect an ontime of the Cerenkov array of ~17% of total time due to the excellent viewing conditions at the observatorio del Roque de los Muchachos.

The primary aim with this array is twofold, an improved time resolution of the shower front as compared to the e.g. detection with the normal stations of the array resulting in a better angular resolution by a factor fo 3 - 5. Secondly, the light distribution of the array can be used to discriminate photon induced showers from hadron induced ones.

Furthermore five imaging telescopes of about 3 meter diameter and with 19 60 cm diameter mirrors will be constructed. At the focal point a camera with 37 pixels of PM's will be installed. The 5 telescopes will be separated by 60 meters each inside the HEGRA array. Both imaging of showers and angular resolution based on timing will be used to identifiy photon sources. The first of the five telescopes will be installed by late summer this year.

The improvement program sketched here will give HEGRA unique capabilities to do very interesting physics in the regime of high energy astrophysics and possibly in the longer term future on particle physics as well.

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