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1 Introduction

In this report we describe a research undertaken approximately three years ago: in it we investigate possible signatures of physics not described by the Standard Model of electroweak and strong interactions. The source of such data is signals obtained from observations of point sources in the sky, typically X-ray binary stars, but also some others, such as the CRAB nebula.

Cosmic ray physics was the most important and, in fact, almost the *only* source of high energy particle physics data until about the middle of this century. Thereafter, most of the new information has come from accelerator based experiments. One's outlook, however, is likely to change again, for the following reasons:

i) It has been realized that *new physics can be most easily discovered in reactions where the uninteresting background* (the “old physics”) *is as small as possible*; the now-classic SLAC-MIT electron scattering experiment and the SLAC positron annihilation experiments leading to the establishment of the quark structure of hadrons and to the discovery of new flavors demonstrate this principle best.

ii) It has been discovered that photons and neutrinos emitted by point sources in the sky are of energies higher than any terrestrial source available until about the end of the first decade of the next century; see, e.g., [1] for a brief summary and references quoted there.

Current accelerator generated γ and ν beams produce interactions with nucleons of $\sqrt{s}$ up to a few dozens of GeV. By contrast, a “typical” EAS event from a point source in a detector like CYGNUS has $\sqrt{s} \approx 2\text{TeV}$. We shall be mostly concerned with energies in this range.

To be sure, the “heavenly accelerators” produce a low flux on Earth (due to their substantial distance from us) and are very erratic in producing what a particle physicist would call a usable beam. Nevertheless, in certain situations, one must be willing to trade luminosity for beam energy — hence the rebirth of particle physics done with extraterrestrial beams (*“ET Particle Physics”*).

This Report summarizes our current view of the subject, with emphasis on the developments which took place during the current grant period. In particular, in the list of references, we printed in **boldface** those articles which either have been completed during the current grant period or their completion is expected before March 31, 1991.

2 Muons as Messengers and the Nature of the Primaries.

Muons are heavy, hence, for all practical purposes, they do not radiate photons while traversing an absorber. As far as we know, their only interactions are electroweak. For this reason, high energy muons carry information about the early stages of a cascade developing in a thick absorber like the atmosphere. Any unexpected behavior of the high energy muon component is, therefore, worth attention; it is likely to signal new physical phenomena at high energies.

In a sense, the rebirth of *ET Particle Physics* is largely due to the discovery of muon-rich EAS associated with CYG X-3 [2]; see also [3,4]. The argument concluding that the existence of such EAS spells trouble for our current knowledge of physics is worth recalling.

i) Assuming that the source has been identified by means of directional and/or timing information, the primary particle must be *neutral*. Even with the most conservative assumptions about galactic or intergalactic magnetic fields, the magnetic diffusion length is a *very small* fraction of the distance at *any* energy currently observed.

ii) Any known particle reaching a terrestrial detector from an identified point source below a laboratory energy $E \approx 10^{17} \text{ eV}$ is, for all practical purposes, *stable*. (The nearest identified point source, HER X-1, is at a distance of about 5 kpc.) Above that energy, neutrons begin to reach us, but most of the data comes from lower energies.

iii) The absence of an observable velocity dispersion, which could wash out the timing information, sets an *upper limit on the rest mass*. Currently this is about 60 MeV; see [4,5].

iv) The primary has a *considerable interaction cross section* with air nuclei. This conclusion can be reached by means of the following argument:

Assume that the incident flux is comparable with the photon flux extrapolated from TeV energies ("No dips and bumps in the primary spectrum"). Then, one expects that, roughly, every incident particle should interact in the atmosphere in order to produce the event rate observed by the Kiel or CYGNUS groups [2,5].

Neglecting nuclear effects such as surface scattering, multiple scattering, Glauber shadowing, *etc.*, one gets a rough estimate of the mean free path (mfp) of any particle incident on an absorber which is independent of the composition of the latter. If the scattering takes place *via* short range forces, the total cross section is just A times the cross section per nucleon,

where A stands for the average atomic number in the absorber.¹ (In this approximation, the incident particle sees just a gas of nucleons.)

Using the value of the atomic mass unit, a numerically convenient form of the expression of the mfp, λ , is:

$$\lambda = 1700/\sigma, \quad (1)$$

where σ stands for the interaction cross section per nucleon, measured in millibarns, and λ is obtained in g/cm^2 . Clearly, under the assumption stated, the mfp must be *smaller* than the absorber thickness above the detector. For CYGNUS (atmospheric depth $\approx 800g/cm^2$) observing the 1986 burst from HER X-1, we obtain $\sigma \geq 2mb/nucleon$.²

Combined with the mass limit quoted above, this is a very important result; *it tells us that the primary giving rise to muon rich EAS cannot be anything else but one of the known light particles.*

One assumes, of course, that there are no other long range forces of substantial strength besides those generated by γ exchange and that production and interaction cross sections of any particle are comparable in magnitude. Both assumptions are well verified in the known realms of particle physics; see [6] and references quoted there.

In other words, it is *very unlikely* that the muon rich EAS are caused by superpartners of known particles, by technihadrons or any other hypothetical particle not discovered in accelerator based experiments so far.

So, what is the primary?

2.1 Photons?

Ochs and Stodolsky [7] pointed out that a *dramatic* increase of the photoproduction cross section could explain the muon content of high energy EAS. However, they did not pinpoint any physical mechanism giving rise to a large increase of the cross section. Such a mechanism has been suggested by Halzen and his collaborators [8]; they pointed out that the small- x behavior of the photon structure function extrapolated from accelerator energies suggests a considerable enrichment in gluons. Even though the extrapolation (like *any* extrapolation) is subject to a considerable amount of uncertainty, it is very likely that such a phenomenon exists at some level. If it does, then at high energies (where small x values are relevant) a γ behaves part of the

¹Notice that this estimate *cannot* be used in estimating cross sections of processes taking place coherently, such as by γ exchange.

²Weaker limits are obtained from detectors located at lower altitudes.

time as a gluon and gives rise to “minijets”, enhancing the muon contents of the EAS.

The basic difficulty with this explanation is that, for it to work as advertised, *some very hard questions involving the conservation of probability have to be answered.*

The issue is the following. A γ incident on a nucleus can, for all practical purposes, do one of two things. Either it creates an electron pair (*via* the well-known Bethe-Heitler process) or it photoproduces some hadrons. From the point of view of the muon contents of the EAS, it is obviously the latter process in which we are interested. However, in computing the amplitude of photoproduction, one has to take into account that there is a considerable amount of absorption in a *large* number of partial waves, due to the Bethe-Heitler process. (To our knowledge, this calculation has never been done properly; *elastic* unitarization has been carried out in an impact parameter framework [10], but that’s only part of the picture.) Even if one just estimates *total* probabilities without regard to quantum effects (see [6] and references quoted there), one finds that, at the energies accessible to presently active detectors, no more than about 20 % of the EAS are μ -rich — in contrast to the observations that *almost all* EAS contain muons [5]. More sophisticated MC simulations of EAS tend to confirm this crude estimate.

2.2 Neutrinos?

This possibility was first raised in ref.[11]; see also [6,9]. It is attractive, because objections related to probability conservation are rendered irrelevant; the cross section $\sigma(\nu + \text{nucleon} \rightarrow X)$ is about 7 orders of magnitude smaller in the Standard Model (SM) than the effect observed. (We do not have to worry about the background!) One also has to take into account that, according to all estimates, the ν flux from a point source is substantially larger than the γ flux; see [12] and references quoted there. Hence, if we can force a ν to interact strongly *somehow*, we have a picture explaining the message carried by the high energy muons in EAS and giving some new insight into physics transcending the bounds of the SM.

Such a mechanism was proposed and worked out to some extent in our papers, starting with [11] and reviewed in [9]. (In fact, this mechanism was first noted as an important consequence of a class of theoretical models describing quarks and leptons as composites of some “preons”.)

We proposed that muon rich EAS arise from a residual strong interac-

tion of neutrinos, as expected in a class of composite models of quarks and leptons.

It is somewhat unfortunate that no one has yet succeeded in constructing a fully satisfactory composite model of quarks and leptons. This does not exclude the existence of such substructure. It may be that we do not have enough experimental data in order to construct such a model; more and better data involving point sources may be of vital importance from this point of view.

We can summarize this section by stating that it is unlikely the particles reaching us from point sources are anything else but some of the known light particles, notably, photons and neutrinos. If so, however, the existence of muon rich EAS cannot be easily explained within the framework of the SM. It is more likely that their existence signals some physical phenomena transcending the bounds of the SM.

3 PeV Absorption Spectroscopy

This is an old subject involving very well known and tested physics. As a consequence, it is a very reliable tool in analyzing the nature of particles reaching us from point sources in the sky. It has been known since 1934 that electron pairs can be created in the collision of two photons. (This was first pointed out by J.A. Wheeler.) As soon as the microwave background was discovered, Jelley and, independently, Gould and Schröder pointed out that high energy photons are absorbed on it and calculated the absorption curve. The modern version of that calculation was carried out (using advanced numerical techniques) by Protheroe [13], whose paper contains a full list of references to earlier works. There is relatively little one can do in order to improve upon Protheroe's results; our aim was to mold the known results into a tool suitable for analyzing large amounts of data concerning a given source [17]. This is achieved by means of the following steps:

1) Define a characteristic length scale connected with photon absorption on the microwave background. This is given by:

$$L = \frac{\pi m^2}{2T^3 \alpha^2}, \quad (2)$$

where m stands for the mass of the electron, α is the fine structure constant and T is the temperature of the microwave background.³ (Numerically,

³All formulae are written in natural units: the speed of light, Boltzmann's constant

$L \approx 2.95 \text{ kpc.}$)

2) Next, define a *universal function*, $\Psi(u)$, as follows.

$$\Psi(u) = \int_0^{X(u)} \frac{v dv F(v)}{1 - v^2}. \quad (3)$$

In the last formula, $X(u) = \sqrt{(u-1)/u}$, and $F(v)$ is given by:

$$F(v) = (3 - v^4) \ln \frac{1 - v}{1 + v} - 2v(2 - v^2). \quad (4)$$

Note that $\Psi(u)$ can be computed once and for all and reused whenever one needs it; this results in some computational economy.

3) Let us, finally, define an *effective inverse temperature*, $\nu(E)$, at which an incident photon of energy E sees the microwave background. (This temperature is measured in units of the rest energy of the electron.) It is given by the formula,

$$\nu = \frac{m^2}{ET}, \quad (5)$$

where E stands for the energy of the high energy photon in the rest frame of the microwave background (for all practical purposes, that is the same as the rest frame of the Earth). Numerically, $\nu \approx 1.02/E$, with E being measured in units of 10^{15} eV . The inverse of the absorption mfp, $l(E)$, of a high energy γ on the microwave background (in units of L) is given as the thermal average of the function Ψ at the effective temperature $1/\nu$:

$$\frac{L}{l(E)} = \int_1^\infty \frac{du \Psi(u)}{\exp(\nu u) - 1}. \quad (6)$$

We found (as did everyone else) that the absorption coefficient peaks around $E \approx 2 \text{ PeV}$ and that the minimum of the absorption mfp is about 7 kpc.

The surprise came when we used this technique to determine the *apparent distance* at PeV energies of the best-known point source, viz. CYG X-3 [14].

Usually we accept as the *true* distance of an object the one measured at energies where we believe we understand the physics underlying the measurement. In this sense, the *true* distance, d , of CYG X-3 is the one measured at a wavelength $\lambda \approx 21 \text{ cm}$, giving $d \approx 11.6 \text{ kpc}$.

What we found is that the *apparent* distance of the same object at a much shorter wavelength, corresponding to PeV energies, is about half of and Planck's reduced constant are equal to unity.

the true distance. *We have to conclude that we do not understand the physics at PeV energies!*

The results of this section can be summarized as follows. We devised a standardized way of computing the absorption of high energy photons on the microwave background. This method yields straightforward distance estimates of point sources at distances larger than about $d \approx 7kpc$ under the assumption that photon regeneration *via* cascading on the microwave background is negligible ⁴ (see [13]) and that all incoming particles are photons.

An analysis of observational data [14] on CYG X-3 suggests that the *apparent* distance of that source at $E \approx 2PeV$ is about half of the true distance. This indicates that a substantial fraction of the primary radiation emitted by CYG X-3 is not absorbed by the microwave background.

4 What Can We Learn from Shower Development?

A preliminary account of this subject was given in [18]; fuller accounts will be found in [19] and [20].

Particles “reaching a terrestrial detector from a distant point source” *do not reach that detector at all*. We have to deduce the properties of the first (or first few) interaction(s) from the properties of the shower generated in the absorber: the atmosphere in the case of an EAS or the atmosphere and rock in the case of an underground detector. In view of the discrepancy between distances obtained for CYG X-3 measured by a standard, astronomical method and at PeV energies (see previous Section), we undertook an investigation of possible anomalously developing showers caused by a new interaction of an otherwise weakly interacting primary. (Lacking specific models of such new interactions, we tried to concentrate upon some general features abstracted from qualitative pictures and analogies drawn with ordinary hadronic interactions.)

As explained in Sec.2, we focus our attention on the behavior of high energy muons; they are likely to carry messages from the highest energy interactions. At this time, we have only preliminary results to report; the description of the details of the computations will be given in [19] and [20].

First, we have to get an idea of the cross section of the new interaction. This was already done in a previous paper [14]. There we found that at

⁴Recent estimates of magnetic fields within the local cluster suggest that this is a fair assumption; we thank Rosemary Wyse for pointing this out to us.

$E \approx 2PeV$ (where the absorption is substantial),

$$\frac{I_\nu}{I_\gamma} \sigma \approx 6mb/nucleon, \quad (7)$$

where I_ν and I_γ stand for the neutrino and photon fluxes respectively, emitted by the source and σ is the cross section of the “new” interaction.⁵ With the usual estimates (see [12]), we conclude that the cross section of the new process is a few mb/nucleon. This is *substantially smaller than either a normal hadronic cross section or the Bethe-Heitler cross section divided by the atomic number of air, but about 10^7 times larger than the SM prediction of $\sigma(\nu + nucleon)$* ; see [6] and references quoted there.

Thus, if the picture outlined above is internally consistent, the “anomalous” showers, on the average, start deeper in the atmosphere than either a hadron or a photon induced one. It is intuitively obvious that this must have some observable consequences. In order to investigate those, we devised two, complementary approaches to the problem.

In both approaches it is assumed that:

i) “new physics” starts at a critical energy, $\sqrt{s} = \Lambda$, with the value of Λ being varied in order to achieve a reasonable agreement with the data; typically we take it to be around a TeV.

ii) It is further assumed that the onset of the new phenomena takes place sufficiently rapidly: below the critical energy, the cross section of the new interaction is essentially zero, above, it is given by its saturation value, around a few mb/nucleon. After the first interaction, one can evolve a shower according to the standard model.

(These assumptions appear to be qualitatively consistent with our findings in the analysis of the absorption anomaly; see [14].) Thereafter, the two approaches differ significantly in their levels of sophistication.

In the first one [19], we construct a crude theory of shower development, in the same spirit as Heitler’s old model of an electromagnetic shower [15]. In this model, “everything happens at its average value”; secondary particles in an interaction share the energy of the primary equally (no leading particle effects), an interaction takes place exactly one interaction mfp after the previous one, and an unstable particle decays exactly one decay mfp after it was produced. Likewise, the multiplicities and the transverse momentum distributions are assumed to be energy independent.

⁵In ref.[14] we actually assumed that the neutrino and photon fluxes are equal; the equation just quoted is an obvious generalization of that estimate.

By contrast, the second approach [20] is a rather sophisticated one; abstracting the properties of a high energy interaction from some prototype composite model, we follow the hadronization process by a MC technique. Similarly, the development of the shower after the first interaction is described using the best techniques available, by simulating both the hadronic and electromagnetic components.

The advantage of this two-pronged approach is obvious. The mathematics of the first approach is very simple. One can easily try out the effects of changing the parameters of the first interaction (the “*new physics*”) and see the qualitative changes in shower development almost instantly. One has to rely upon the second, sophisticated approach for the discovery of subtler effects or for a reliable description of the resulting particle distributions. In order to achieve that, however, more computing time is needed. One tends to try out “wild guesses” in the first approach and follow up promising leads in the second one.

After a few initial runs, there seem to be two salient features emerging.

First, we find that the lateral distribution of muons tends to be narrower than in normal showers (either photon or hadron initiated ones).

Second, one finds the number of energetic muons to be somewhat above the value naively expected. If confirmed by further runs, both features can be important; they would enable observers to pin down showers initiated by primaries which do not behave according to the Standard Model. (The main issue at this point is whether these phenomena are sufficiently *robust*, i.e. independent of detailed assumptions made about the nature of the first interaction⁶.)

Another feature of the muon rich (“anomalous”) showers one should be able to pinpoint rather easily is that, in many respects, *besides their muon content* they tend to behave like hadron initiated showers. This means, *inter alia*, that their electromagnetic (EM) component resembles the EM component of a normal cosmic ray shower. Due to the fact that the latter give rise to a *line source* of the EM component (instead of a point source as in the case of γ or electron induced showers), after the very early stages of development, the effective age parameter, s_{eff} , of the EM component settles down to a nearly constant value. The rule of thumb is that, on the average,

⁶At the ISVHCRI meeting, (Tarbes, France, July 1990), in response to our talk [17], G.B. Yodh pointed out that muon rich EAS associated with the 1986 burst of HER X-1 appear to produce a narrower muon distribution than ones initiated by hadrons. If confirmed, such evidence may contribute to the picture of “new physics” emerging from these phenomena.

$s_{eff} \simeq 1.25$ [16]. The “anomalous” EAS generated by the new interactions should have a comparable EM component⁷.

5 Conclusion: Where Do We Go from Here?

Based on a *very limited set of data*, there is, nevertheless, an internally consistent picture emerging. Its main features are:

- a) There is a component of the high energy radiation emitted by some (all?) point sources which is not absorbed by the $3^\circ K$ background.
- b) Its cross section on nucleons is substantial, but smaller than a normal hadronic cross section (and smaller than an EM cross section per nucleon would be on an air nucleus).

Some considerations suggest that the anomalous showers are not caused either by a so far undiscovered particle or by a photon. However, at this stage, any suggestion concerning the nature of the new phenomena constitutes, at best, a set of theoretical working hypotheses. What is needed, in our opinion, is better detectors and a *new style of observation*⁸. Here are a few items on the theorist’s (admittedly biased) list of *desiderata*, following our presentation given at the Tarbes meeting [17]:

- In order to discover “new physics”, muon detectors and conventional EAS detectors should be used in conjunction. Either a muon detector or a surface array by itself is of little use for the purpose of discovering “new physics”. While muon detectors receive the message about the interactions at the highest energies, the total energy is an important parameter; it can be determined only from a study of the EM component.
- Observations should be recorded and stored so as to be available for later use. (Data of little significance today may become important when put together with those of other observers.)
- One should contemplate the observation of as large a number of sources as permitted by the location of any given detector. UHE sources

⁷In a private communication, Jordan Goodman remarked that the EM component of most of the EAS associated with the HER X-1 burst of 1986 tends cluster around $s_{eff} \simeq 1.25$. This may or may not be a coincidence; however, this point deserves further consideration.

⁸and the cooperation of the point sources in the sky, but, *alas*, we have no control over that ...

tend to be erratic: any dedicated detector built to observe one or two sources or one particular phenomenon only is likely to run idle most of the time.

- One should contemplate observing the sources under various absorber depths. (This is achieved by observing at various zenith angles.)
- Data should be collected without bias as to the nature of the EAS observed. Trying to find a source by forcing the hardware to select, e.g., muon poor showers only is an obsolete method; such a selection should be done at the time of the analysis rather than at the time of data taking⁹.
- Energy determinations should be made more precise. Detectors should have as broad an effective energy range as possible with either software switchable thresholds, or, better still, software selected windows. Small detectors of the past had no choice but to present all data observed above a built-in threshold. This is not *or, at least, should not be* the case for the detectors of the future.

We fully realize that some of the items listed above are being implemented in detectors currently in the planning stage. Nevertheless, it is useful to compile such a list. In essence, it serves to emphasize the implementation of two of the time-honored methods of searching for new phenomena in particle physics:

- Multicomponent neutral beams are separated into their components by means of varying the thickness of the absorber.
- The energy scale for the onset of the new phenomenon (hence, by the use of elementary kinematics, its distance scale) is determined by varying the beam energy.

The progress made during the current grant period can be briefly summarized as follows.

1. We made further progress in establishing that the data exhibit an anomaly, which, in all likelihood, points to physics not described by the Standard Model.

⁹The problem here is just the opposite one faces at modern accelerators; instead of the worry of detector saturation, one has to attempt to save every bit of the scarce data obtainable.

2. We identified certain properties of extensive air showers by means of which one can further study the nature of the new phenomena.
3. We carried out theoretical calculations on the basis of which one will be able to study the parameters of the new phenomena, such as the characteristic distance at which these phenomena occur, the energy of their onset, etc.

Due to the scarcity of data available, progress is somewhat slower than it would be desirable. We maintain active contact with many of the groups of observers in order to learn about new data as they become available; also, in order to exchange ideas about the ways of extracting useful *particle physics* information from the available data.

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