OBSERVATION OF MUONS FROM CYGNUS X-3 IN THE NUSEX EXPERIMENT

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INTRODUCTION

Ground based observations by means of Cerenkov light detectors and air shower arrays have established that Cygnus X-3 is a powerful source of high energy particles. The detection of a 10^{15} eV signal was first reported by the Kiel experiment. Air showers with large age parameter were accepted in order to select those generated by primary γ-rays. At variance with the expectation, the muon density associated with these events was found to be surprisingly high. This puzzling result stimulated a temporal analysis of the muons recorded in NUSEX(*) coming from the region around the source. A positive signal was found suggesting the presentation of the result at this Conference. The analysis of the data recorded during about 2.4 years of effective working time was presented at the First Symposium on Underground Physics (St. Vincent, Italy) and then published [1]. In the paper sent to this Conference a fine tuning of the period has been presented and the energy spectrum of the muons from the Cygnus X-3 direction derived assuming consistency between NUSEX and SOUDAN results [2]. Here I account for a refined and upgraded analysis of the same events.

THE APPARATUS

The NUSEX (Nucleon Stability Experiment) detector is located in the Mont-Blanc tunnel (45.9° N latitude, 6.9° E longitude) at a vertical depth of about 5000 hg/cm² of standard rock.

It consists of a cube of 150 t mass and 3.5 m side, made of 136 horizontal plates of 1 cm thickness, interleaved with planes of tubes having 1 cm x 1 cm cross section, operated in the limited streamer mode.

This paper is the written version of the talk given at the 19^{th} ICRC, La Jolla, California (USA), 11-23 August 1985

Minimum trigger requirements are that either four contiguous planes or a pair of contiguous planes plus a group of three other contiguous ones are fired simultaneously.

Tracks are accepted for reconstruction only if the number of crossed planes is at least 10. This criterium defines a fiducial volume of well defined acceptance and detection efficiency practically equal to unity.

NUSEX was planned to search for proton decay working as a digital calorimeter with excellent tracking capability. Typical errors in reconstructing tracks satisfying the above mentioned criterium are $\sigma_\theta \sim 1$mr and $\sigma_\phi \sim 2$mr. The two track resolution is better than 2 cm.

A detailed map - contour lines at 10 m - of the rock overburden allows us to associate to each direction a slant depth with an accuray $\Delta h/h < 1\%$.

These properties make NUSEX a well suitable apparatus to perform muon physic underground in the depth range 4600 - 10.000 hg/cm ^{2}.

MUON PHYSICS

An analysis of the muon events was started to study the single muon intensity-depth distribution, multiple muon rates, stopping muons, narrow angle anisotropies. Data on single and multiple muons have been presented at this Conference [3]. The vertical muon intensity is reported in Fig. 1 together with the intensity points measured with the spark chamber apparatus located in another laboratory of the Mt. Blanc tunnel. The intensity versus depth is very well represented by the relation

$$I\mu(h) = (7.63 \pm .48) \cdot 10^{-7} \cdot \exp(-h/810.44 \pm .84)\ \mathrm{cm^{-2} s^{-} sr^{-1}} \qquad (1)$$

The angular distribution underground is in good agreement with the expected one. (Calculations of the angular enhancement functions at different depths are given in [4]). The contribution from direct production is found to be negligible, not exceeding a 3-4 % of the total up to 8000 hg/cm^2. In conclusion, muons physics in NUSEX is well understood and predictions of muon rates in each direction can be made with high reliability.

ANALYSIS OF THE CYGNUS X-3 DATA

During the period 1 June 1982 to 31 January 1985 21,700 single muons with zenith angle up to 75° have been recorded satisfying the acceptance criterium. With this angular cut Cygnus X-3 is observed for 64% of the total time.

In a cone of 4.5° half angle aperture centered around the source [δ = 40.9 α = 307.9] we find 142 events. The time of each event is reduced to the barycenter of the solar system and then folded modulo 4.8 h using the Van der Klis and Bonnet-Bidaud quadratic ephemeris [5]. The phase diagrams for two different binnings are shown in Fig. 2. We observe 31 events in the phase interval 0.7 - 0.8 against an average off-source background of events11.32 ± .21. The associated fluctuation probability that this effect occurs by chance is less than 10^{-4}.

The quoted phase values found in TeV γ-ray observations of Cygnus X-3 occur in the range 0.6 - 0.8 [6]. This agreement with previous observations in the same energy region is not sufficient to claim a physical effect. It is not obvious that over an extended period of time no biases were introduced in data taking, so that it is necessary to verify that the probability of detecting a muon does not depend on phase or on direction, due to details of the experimental procedure. For example the Cygnus X-3 orbital period is almost exactly 1/5 of the sidereal day. If the period were an exact fraction each phase should be "seen" always in the same five directions (θ,ϕ), in such a way generating a strong correlation phase / acceptance / depth. Fortunately is not like that. A given phase precesses over the detector 2.1 times/year producing an average effect for long time measurements. This point has been checked by calculating the exposure relative to each phase bin for Cygnus X-3 and for other directions in the same declination band. 27 contiguous cones of half angle aperture 4.5° have been selected in the ± 4.5° off-Cygnus declination band, covering 321.5 degrees in right ascension around the source position. For each of the 28 cones (Cygnus X-3 + background ones) the path in the sky has been followed during the entire data taking period. At each time there is a well defined phase (for a given ephemeris), direction, acceptance area, and depth. Taking into account only the periods in which the apparatus was ON the exposure as a function of the depth for each phase and cone has been calculated. In this way 280 very similar exposures have been generated. As an example the "Cygnus X-3 profile" for two phases is shown in Fig. 3.

To obtain the expected counting rates in each phase bin and cone the exposure has been calculated folding the acceptance with the angular distribution of conventional muons and with the intensity depth relation (1).

The measured phase distribution of the events in the 27 background cones is found in excellent agreement with expectation, no fluctuation is observed with probability less than 10^{-3}. In Fig. 4 the phase distribution of all background events is shown. It is well reproduced by the calculated one and results consistent with unformity (χ^2 = 9.78, $P(>\chi^2)$ = 36.8%). The predicted mean for each bin is 313 against an experimental value 306 ± 6. In the Cygnus cone the expected background is 11.9 events per bin, compared with 12.3 ± 1.3 observed. A χ^2 test on the phase histogram uniformity about the off-source mean yields χ^2 = 30.5 [$P(>\chi^2)$ = $3.6 \cdot 10^{-4}$] while the phase histogram outside the interval .7 - .8 is consistent with noise (χ^2 = 9.73, $P(>\chi^2)$ = 28.4%).

Thus we can conclude that the muon distribution in the same declination band as Cygnus X-3 follows the expected one. No non-random dependences on phase or on direction have been found in the background data, implying that there are no priviliged phases or direction. Only in the cone centered around Cygnus X-3 is a deviation from the expectation found due to an enhanced flux in the phase interval 0.7 ÷ 0.8. This excess appears to be "genuine", in that it originates either by some physical effect or by a statistical fluctuation. The χ^2 test for uniformity, the probability of fluctuation in any one of the ten bins ($6 \cdot 10^{-5}$) and the confidence level for enhanced flux (99.95%) can be considered in order to give an estimate of the statistical significance of the excess.

ANALYSIS OF THE PERIOD

The period used in the above analysis comes from a fit of the X-ray data recorded in different satellite missions [5]. We checked this period from the muon data themselves alone.

In general we expect the best period to give the narrowest peak of one or more adjacent bins according to the binning used. If a phase diagram in 10 bins is used the best period should correspond to that giving the maximum concentration of events in one bin. This search is performed moving the period and its derivative in steps of $4 \cdot 10^{-7}$ d and $2 \cdot 10^{-10}$ respectively and looking at the same time for the maximum value of χ^2 and the minimum of the probability of fluctuation.

A change in period of $4 \cdot 10^{-7}$ d gives a shift for our data recorded between June 82 and January 85, of 0.42 to 0.052. A change in the period derivative of $2 \cdot 10^{-10}$ gives a phase shift in the range 0.050 to 0.066. In the scanning over the period the derivative has been set to the ephemeris value.

The result is shown in Fig. 5 where χ^2 and fluctuation probability are plotted for both period and period derivative scannings. The best values derived from muon experimental data on the basis of these tests coincide with the x-ray ephemeris ones. The phase histogram in 20 bins shows that the excess is concentrated in a phase width of about 29'.

ANGULAR SPREAD

The previous analysis has been performed looking in a cone with half opening of 4.5° because this aperture appears necessary for full containement of the signal. This effect is shown in Fig. 6 where the signal is plotted as a function of the cone aperture. While the background "out-phase" increases as the solid angle and the counts in these phase bins follow the expectation, the count in the bin .7 - .8 shows an increasing positive excess up to about 4.5°. For larger opening angles the entries follow the expected background.

The dipersion of the signal is shown in Fig. 7. Using a gaussian distribution for point source resolution a mean angle of about 2.5° is required to get a fair agreement. It seems at variance with the expectation because the angular resolution of the apparatus is better than 1° ($\sigma_\theta \sim$ 1mr, $\sigma_\theta \sim$ 2 mr, misalignement < .3°) and the multiple scattering is estimated to contribute with a mean dispersion angle of $\sim$ .6° (Fig. 8,9).

This dispersion cannot be easily explained by transverse momentum acquired at production, 1° corresponding to about 100 GeV for energetic muons detected in NUSEX. Thus this result remains at moment an unresolved question.

MUON SPECTRUM

The depth distribution of the 111 "off phase" events follows the one expected for atmospheric muons. Thus from the 31 "in phase" events we subtract the background events according to the depth distribution expected for atmospheric muons so obtaining the distribution for the 19 excess events given in Fig. 10. Only 1 event is found in the depth region around 7000 hg/cm^2 corresponding to the maximum of the exposure. This result rules out the hypothesis of neutrino-induced events because in such a case the muon depth distribution should follow the exposure profile. The events have been binned to obtain the intensity at four different depths. Using the calculated exposure for isotropic or conventional (according to a "$\sec\theta$ law"as calculated in [4]) angular distribution we find the intensity values shown in Fig. 11. A typical flux (averaged over the Cygnus X-3 period) at a depth $\sim 5000\ hg/cm^2$ (muon threshold $\sim$ 3 TeV) is $5 \cdot 10^{-12}\ cm^{-2}s^{-1}$.

The depth interval covered by our data and their statistical uncertainty prevent one from obtaining the muon energy spectrum from the NUSEX events alone. This is possible if, assuming consistency between the fluxes measured in the two experiments, also the SOUDAN point at 1800 hg/cm^2 is used [7]. Folding a power spectrum with the survival probability P(E,h) [8] we obtain the muon energy differential spectrum corresponding to the measured intensities as :

$$dI/dE\ (cm^{-2}\ s^{-1}\ GeV^{-1}) = \begin{cases} (3.9 \pm .7) \cdot E^{-(2.3 \pm .2)} & \text{isotropic distribution} \\ (8.8 \pm 1.6) \cdot E^{-(2.4 \pm .2)} & \text{"}\sec\theta\text{" distribution} \end{cases}$$

The muon integral spectrum is found to be

$$I(cm^{-2}s^{-1}) = \begin{cases} (3.0 \pm .6) \cdot 10^{-7}\ E^{-(1.3 \pm .2)} \\ (6.3 \pm 1.2) \cdot 10^{-7}\ E^{-(1.4 \pm .2)} \end{cases}$$

respectively. In spite of the large uncertainty in deriving this result the spectrum seems much flatter than the ordinary atmospheric muon one

($\gamma \sim 2.71$) and not far, in slope and absolute intensity, from the primary flux attributed to photons from Cygnus X-3 in the range 10^{12}-10^{15} eV. (Fig. 12).

CONCLUSIONS

The main steps of the analysis of the muon events detected in the direction of Cygnus X-3 have been reported in order to show the consistency of the data both internally and with expectation, and in particular that no biases were introduced in data taking or in the analysis procedure. From Cygnus X-3 the NUSEX experiment picked-up signals showing the precise period of this binary system and with a phase distribution consistent with the ground-based measurements. The probability that this signal was generated by chance is estimated to be 10^{-4}.

If the result is right, it is difficult to account for these data since conventional interactions of conventional particles are unable to explain in a unique consistent picture both surface air shower and muon underground fluxes [9].

Continued measurements by different detectors are requested to decide unambigously on the existence of the effect. In order to isolate a small flux of muons associated with Cygnus X-3 from background muons the dimension, angular resolution, and location of the apparatus assume a crucial importance. In fact present results seem to indicate a muon generation via prompt production, hence with flat energy spectrum and isotropic distribution, thus penalizing experiments at shallow depth or looking at high depth through large zenith angles. In this respect the continuous collection of data in the NUSEX experiment, planned at least up to the end of '86, could add decisive information to the solution of the Cygnus X-3 problem.

References

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Figure Captions

Fig. 1 : Muon intensity underground at Mt. Blanc.

Fig. 2 : Phase distribution for muons arriving within 4.5° of the direction of Cygnus X-3 : a) plot in 10 bins b) plot in 20 bins.

Fig. 3 : Exposure for Cygnus X-3 integrated over the running time and averaged over the total phase (-phase 0.75, --- phase 0.005).

Fig. 4 : Phase distribution of the 3057 muon events recorded in the 27 cones used to evaluate the background. The same phase distribution as calculated by simulation is shown.

Fig. 5 : χ^2 and probability of fluctuation as a function of a trial period (a) or period derivative (b). The zero of the scale indicates the values determined from X-ray data [5].

Fig. 6 : The excess in the phase bin .7 - .8 plotted versus the cone half opening.

Fig. 7 : Scatter plot in declination and right escension for the 31 events in the phase bin .7 - .8.

Fig. 8 : Error distribution for zenith (θ) and azimuthal (ϕ) angles of tracks reconstructed in NUSEX.

Fig. 9 : Distribution of the angle between muon pairs in NUSEX: d is the distance between the tracks.

Fig. 10 : Depth distribution for the 31 "in phase" events. The distribution of the 111 "out phase" events is also shown.

Fig. 11 : Underground intensity of muons from the direction of Cygnus X-3 (NUSEX and SOUDAN results).

Fig. 12 : Integral energy spectrum of muons from the direction of Cygnus X-3 compared to the estimated flux of "γ-rays" [6].

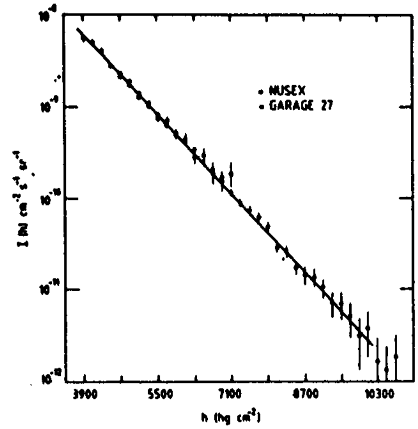

FIG. 1

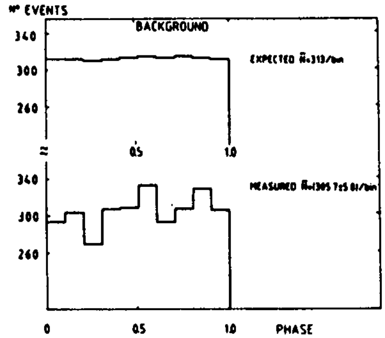

FIG 4

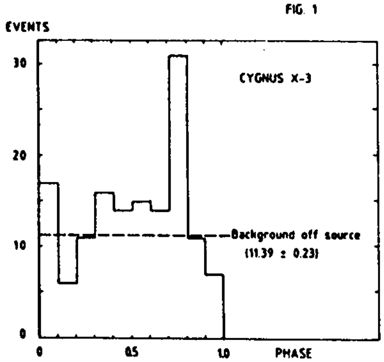

FIG. 2a

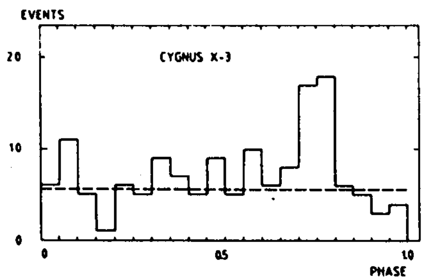

FIG. 2b

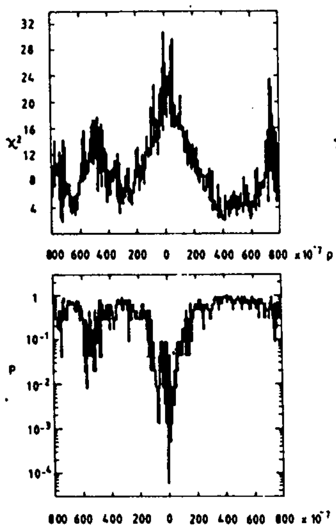

Fig 5a

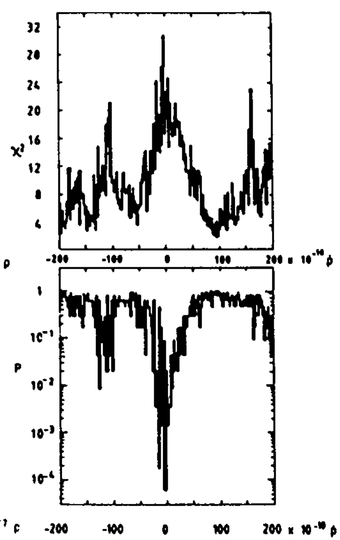

Fig 5b

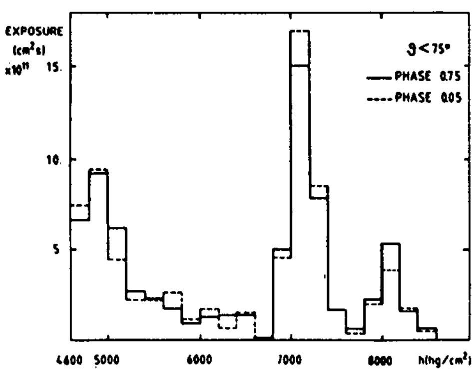

Fig 3

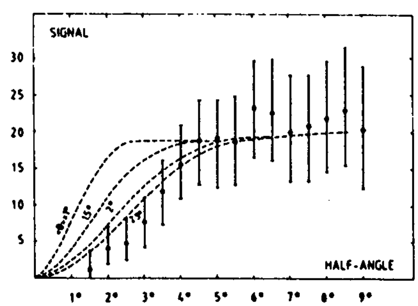

Fig 6

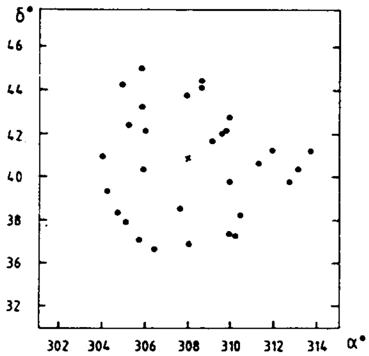

FIG 7

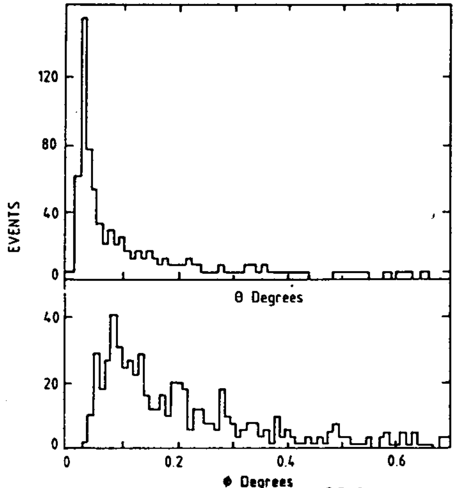

FIG. 8

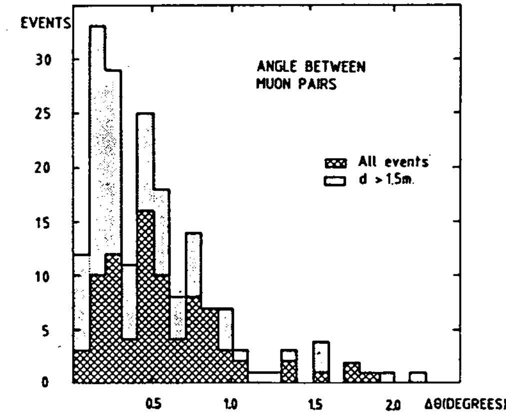

FIG. 9

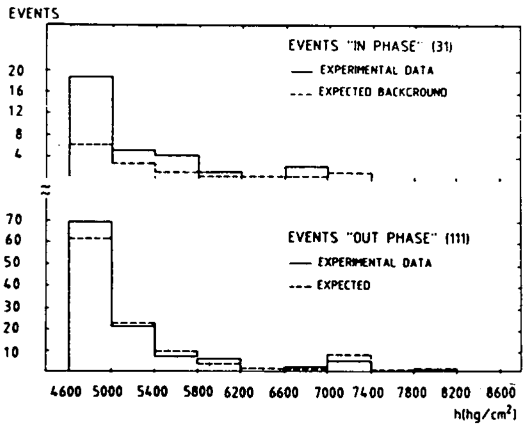

FIG. 10

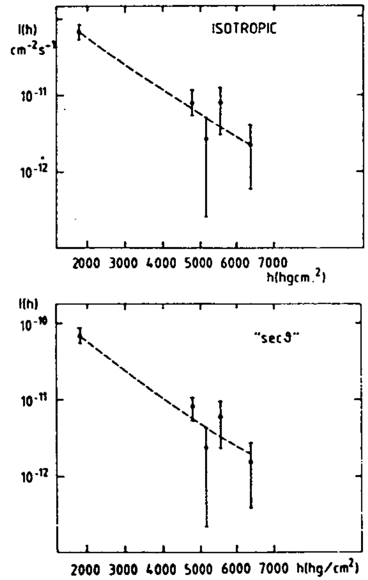

FIG 11

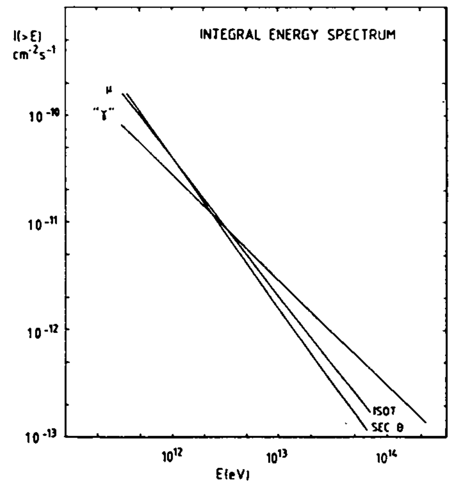

FIG 12