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Presented by Sergio Petrera

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The MACRO detector is sensitive to wide range of ionizing massive particles in cosmic rays. These include "nuclearites" or strange quark matter. The negative result of a search lasting about 20 months using 1/12 of the detector has yielded a flux limit of $1.1 \times 10^{-14} cm^{-2} sr^{-1} s^{-1}$ for strange matter with mass $10^{-10}g < m < 0.1g$. For $m > 0.1g$, the limit is $5.5 \times 10^{-15} cm^{-2} sr^{-1} s^{-1}$. Since the velocity range of nuclearites to which MACRO is sensitive extends down to near the escape velocity of the earth, the flux limit not only applies to nuclearites of galactic or extra-galactic origin but also applies to nuclearites that are trapped in the solar system.

1. INTRODUCTION

The possibility that strange quark matter may be absolutely stable and may be the true ground state of QCD for a given baryon number has created much interest in last few years.[1-5] Within the range of presently allowed QCD parameters, such stable strange matter may have a mass ranging from a few GeV to the mass of a neutron star. Since the possible mass of strange matter can be anywhere within such a wide region, to detect it requires very different experimental techniques in different mass regions. These include techniques ranging from mass spectrometer searches in earth materials to searches of natural disasters caused by large pieces of strange matter hitting the earth.[3,4] Several cosmic ray searches have been carried out at different altitudes using different techniques, including scintillator detectors,[6,7] ancient mica,[8] plastic track etch detectors,[9-11] balloon flight[12] and a gravitational wave detector.[13]

MACRO (Monopole Astrophysics Cosmic Ray Observatory) is an underground detector situated in Hall B of the Gran Sasso Laboratory in central Italy at a depth of about 4000 m.w.e.[14] Although MACRO's primary physics goal is to search for magnetic monopoles, its monopole detection system will also detect cosmic ray strange quark matter that reaches the MACRO depth.

2. THE DETECTOR

The part of the MACRO detector used in this work, which is only 1/12 of the whole detector, consists of 10 layers of streamer tubes surrounded by two horizontal walls of scintillator counters on the top and bottom and three vertical walls of scintillator counters on the west, east and north sides. The dimension of this part of the detector is about 12m long, 12m wide and 4.5m in height.

Two types of slow particle triggers are employed in this search. The first slow particle trigger (Type I) is based on the time of passage of particles through a scintillation counter. This trigger system recognizes wide pulses or slow trains of single photoelectron pulses generated by slow particles and rejects large and short pulses caused by muons and radioactivities. The second slow particle trigger (Type II) is based on the time of flight between different walls of scintillators. This system is simply a slow coincidence between walls vetoed by a fast coincidence between them. When a slow particle trigger occurrs, the waveforms of both the anode and the dynode of each photomultiplier tube (PMT) are recorded separately by two waveform digitizers; each covers a different dynamical range.

The muon triggers are also used in this search for fast nuclearites. When a muon trigger occurs, the pulse height and the time of each PMT signal are recorded by ADCs and TDCs. Streamer tube hits are also recorded and then used to construct the tracks. Fast monopoles and strange matter can be recognized by their unusually high ionization yield. The muon trigger covers the β range from 10^{-2} to 1.

3. LIGHT YIELD OF STRANGE MATTER IN SCINTILLATOR

De Rujula and Glashow have calculated the light yield of strange matter traversing transparent materials based on the black body radiation of the heated track. The light yield per unit length of the track is given by[3]:

$$\frac{dE_\gamma}{dx} = \frac{a}{6\pi^2\sqrt{2}}\,\omega_{max}^{5/2}(m/n)^{3/2}v^2 \tag{1}$$

where $a = \pi R_0^2$ is the cross section area of the nuclearite, m is the mass of a the molecule of the material, n is the relevant number of submolecular species in a molecule, and ω_{max} is the maximum frequency for which the material is transparent.

For scintillators, however, the photons absorbed by the wave-shifters are not lost. Instead, they are re-emitted at lower frequency in the transparent region. For this reason, $\omega_{max}^{5/2}$ in equation (1) should be replaced by:

$$\begin{gathered}(\omega^0_{max})^{5/2}+ \\ +\sum_{i=1}^{N}(\bar{\omega}^{eN}/\bar{\omega}^{ai})Q_i\cdot Q_{i+1}\cdots Q_N[(\omega^{ai}_{max})^{5/2}-(\omega^{ai}_{min})^{5/2}]\end{gathered} \tag{2}$$

where ω^0_{max} is the maximum frequency for which the scintillator is transparent, N is the number of wave-shifter components, ω^{ai}_{max} and ω^{ai}_{min} are respectively the maximum and minimum absorption frequency of ith shifter, Q_i is its quantum efficiency, $\bar{\omega}^{ai}$ is its average absorption frequency and $\bar{\omega}^{eN}$ is the average emission frequency of the last wave shifter (which emits in transparent region). For the MACRO scintillator, expression (2) gives about $(4.35eV)^{5/2}$, considerably larger than $(\pi eV)^{5/2}$, the typical number for a transparent material.

Since scintillator oil is a mixture of organic molecules of various sizes, it is not possible to determine m and n separately. The ratio m/n, however, can be easily determined using the H to C ratio $R_{H/C}$.

$$m/n = \frac{m_C + R_{H/C}m_H}{1 + R_{H/C}} \tag{3}$$

where m_C and m_H are the mass of carbon and hydrogen atoms respectively.

Using equations (1) and (3) and replacing $\omega_{max}^{5/2}$ by expression (2), we calculated the light yield of MACRO scintillator for strange matter of different masses. The results are shown in Fig.1, together with the 90% trigger efficiency contours on the light yield versus β. The 90% trigger efficiency contours are measured directly using simulated events obtained by driving LEDs with pulses of variable lengths and heights. Considerable improvements in the detector were made during summer 1989 and the slow particle trigger sensitivity increased by one order of magnitude, as show in Fig.1. It is clear, the MACRO detector is sensitive to nuclearites as slow as $5 \times 10^{-5}c$, close to the escape velocity of the earth.

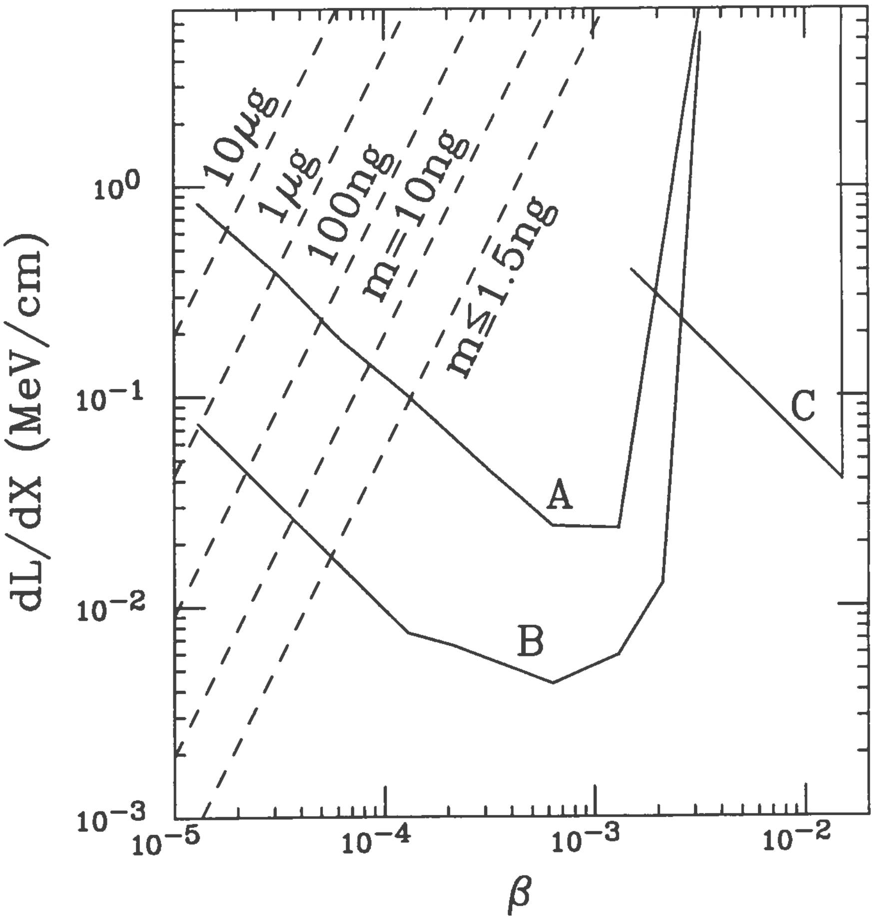

Figure 1.
Light yield of nuclearites in MACRO scintillator as a function of velocity ($\beta = v/c$) for different masses of nuclearites (dashes). The solid curves are the 90% trigger efficiency contours of MACRO slow particle trigger system. (A):Type I trigger based on time of passage in one scintillator counter before summer 1989; (B):The same Type I trigger after summer 1989; (C):Type II trigger based on the time of flight between scintillator counters.

4. THE SEARCH AND THE RESULTS

Slow and fast monopole searches have been conducted by several groups in our collaboration using different methods and data sets. The data sets consist of a 3 month run in Spring 1989 and a run from October 1989 to April 1991.

For trigger type I data, we required at least two scintillator walls to have triggers and this cuts the data sample to only a few hundred events. Those events were then visually scanned to search for wide pulses or long pulse trains characteristic of a slow particle passing through the detector[15]. We found only two events in which both triggering scintillator walls have pulse trains, but none of them has consistent light levels and photoelectron fluctuations. For the data set of Spring 1989, a search requiring only a single face trigger was also performed[16] and this method increased the acceptance by about a factor of 2.

For trigger type II data we visually scanned all the 930 events in the data set of Spring 1989. We found 29 stopping muons and 264 muon events that somehow fooled the muon veto circuit. The rest of the events are all due to electronic noise and none of them exhibits pulse trains or wide pulses expected from a slow particle passing through the detector. The analysis of the rest of type II trigger data (after summer 1989) is not yet complete.

Fig.2 shows the waveform of one of the *best* slow particle candidates we found in type I trigger data compared with the waveform of an LED simulated event and the Monte Carlo

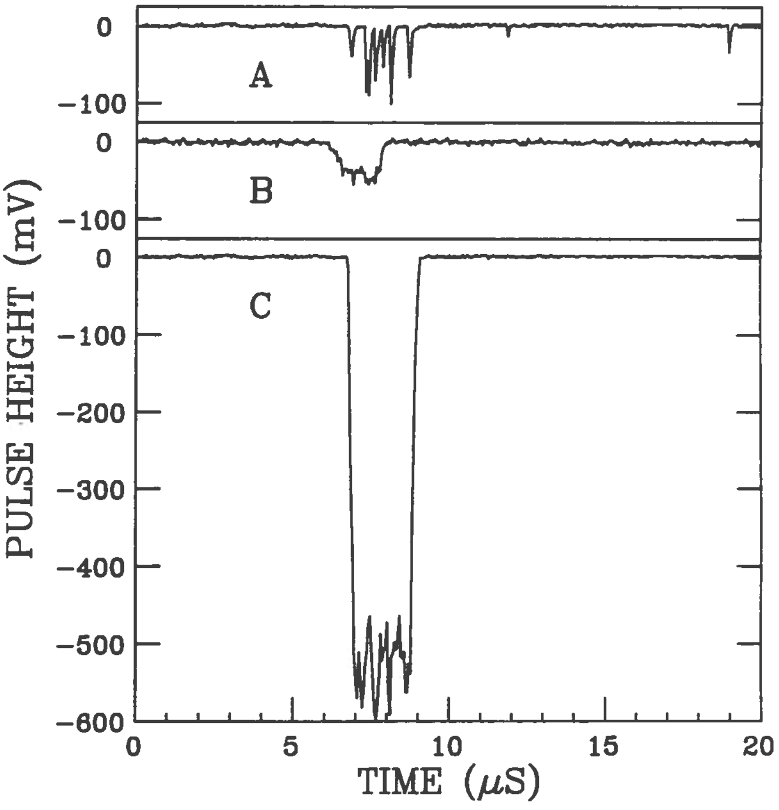

Figure 2.

(A):The waveform of the *best* slow particle candidate we found. (B):The waveform of an LED simulated event having roughly the same signal charge as (A). (C):The Monte Carlo simulated waveform of a nuclearite with $\beta = 3 \times 10^{-4}$. All the waveforms are drawn in the same scale.

simulated waveform of a nuclearite with $\beta = 3 \times 10^{-4}$. All the waveforms are drawn in the same scale. The candidate waveform (A) shows a pulse train, but it is too spiky to be consistent with a slow particle. The waveform of a slow particle should look like waveform (B) which has about the same light level but is much smoother and the small fluctuations are consistent with the photoelectron statistics. Furthermore, if waveform (A) were due to a nuclearite, its velocity would be $\beta = 3 \times 10^{-4}$ based on the length of the pulse train. At this velocity, however, a nuclearite should generate much more light and produce a waveform that looks like (C), quite different from waveform (A). We also checked the time of flight between two scintillator walls and the duration of the pulse train in each wall and found that they are not consistent with a slow particle passing through the detector.

The fast monopole search was performed on our muon trigger data. In this search, we required consistency of streamer tube tracking and scintillator hits and then derived dE/dX in each scintillator counter after correcting for PMT saturation and light attenuation. The scatter plot of dE/dX in one scintillator wall versus dE/dX in another wall is shown in Fig.3. A fast nuclearite ($\beta > 10^{-2}$) should have a dE/dX several orders of magnitude larger than that of a typical muon. As can be seen in Fig.3, no event having a dE/dX in both walls greater than 6 times that of an ordinary muon were found.

The acceptance of the detetor for all the searches are calculated using Monte Carlo programs. The live times are ensured by constant recording of muons and other types of events as well as a calibration run that automatically starts every 4 hours.

The combined flux limits from all these searches are shown in Fig.4 as a function of the nuclearite velocity. The MACRO search covers the velocity range from $\beta = 1$ down to $\beta = 5 \times 10^{-5}$. The MACRO limit, therefore, not only applies to nuclearites of galactic or extra galactic origin but also applies to nuclearites that are trapped in our solar system.

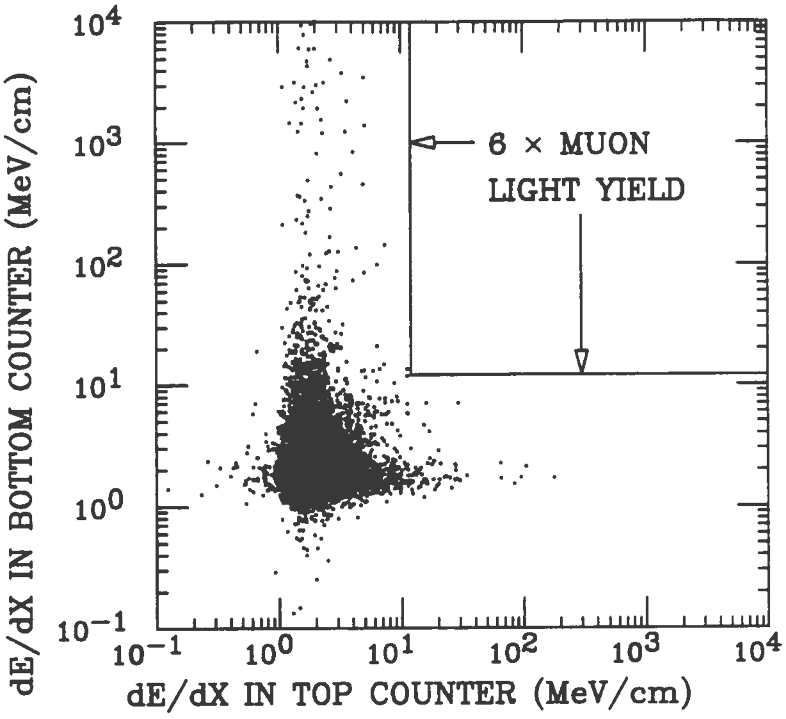

Figure 3.
Scatter plot of dE/dX in one wall versus dE/dX in another wall for muon events. There is no event having dE/dX in both walls greater than 6 times that of an ordinary muon.

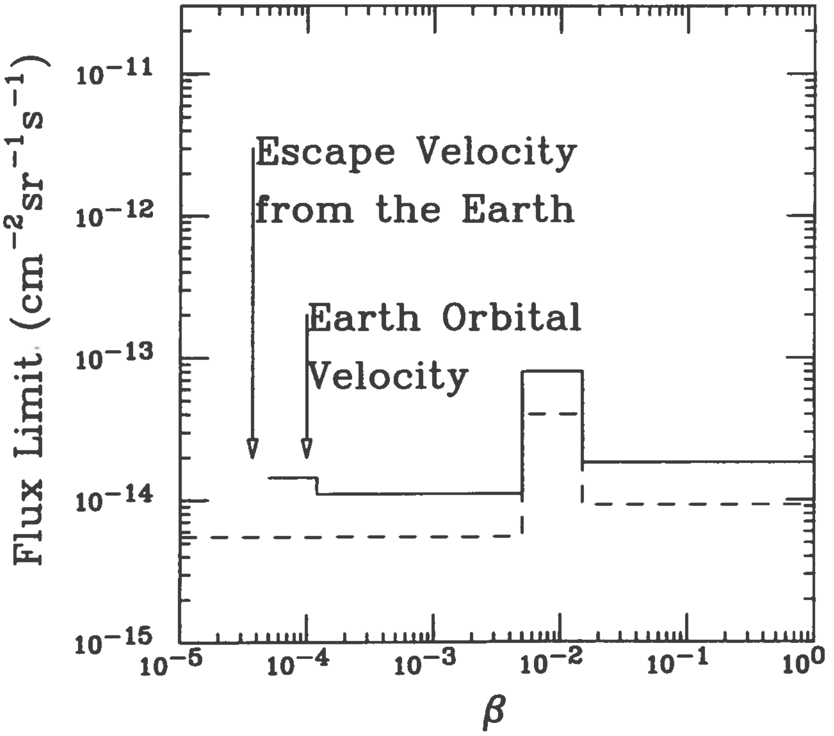

Figure 4.
Nuclearites flux limit as a function of $\beta = v/c$ from the combined several MACRO searches. Solid line is for small nuclearites smaller than 0.1g (not able to penetrate the Earth). The dashed line is for nuclearites that can penetrate the Earth (greater than 0.1g).

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