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PROCEEDINGS SUPPLEMENTS

COSMIC RAY SEARCH FOR STRANGE QUARK MATTER WITH THE MACRO DETECTOR

THE MACRO COLLABORATION

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The MACRO detector is sensitive to any fast or slow highly 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 $10^{-11} g < m < 0.1g$. 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 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.

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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 searches using 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 meter water equivalent.[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 scintillator 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 scintillator counters. This system is simply a slow coincidence between walls vetoed by a fast coincidence between them. When a slow particle trigger occurs, 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 muon tracks. Fast monopoles and strange matter can be recognized by their unusually high ionization yield.

3. LIGHT YIELD OF STRANGE MATTER

De Rujula and Glashow have calculated the light yield of a nuclearite 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 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:

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

where ω_{max}^0 is the maximum frequency for which the scintillator is transparent, N is the number of wave-shifter components, ω_{max}^{ai} and ω_{min}^{ai} 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 sifter (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 effective ratio m/n, however, can be easily determined using the H to C ratio $R_{H/C}$.

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

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 plane. 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. The MACRO detector is sensitive to nuclearites as slow as $5 \times 10^{-5}c$, close to the escape velocity of the earth.

It should be noted that the above calculations depend sensitively on the apparent size of the nuclearites and other parameters which are still not well understood. For this reason, the above calculations should be regarded as an estimate of the correct order of magnitude. However, since only the black body radiation is considered in the calculation, the result is likely to be overly conservative. When the effect of the direct excitation of the scintillator is taken into account, the light yield may be much larger than we have calculated here and it is possible that the actual sensitivity of the MACRO detector extends beyond the escape velocity of the earth, or even the orbital velocity around the earth.

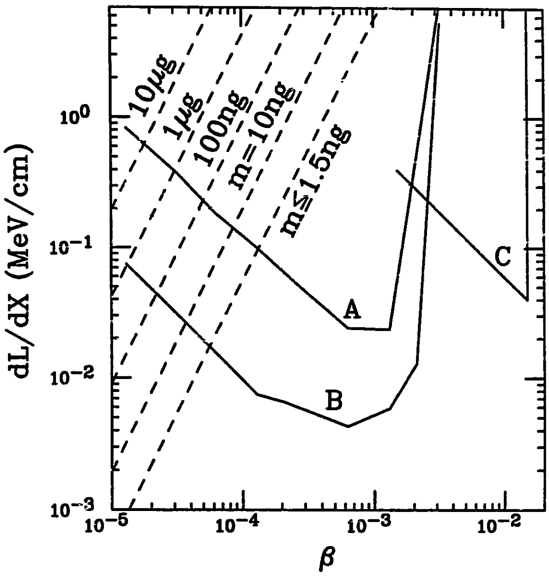

FIGURE 1
Light yield of a nuclearite in MACRO scintillator as a function of velocity ($\beta = v/c$) for different masses (dashes). The solid curves are the 90% trigger efficiency contours of MACRO slow particle trigger system: A)Type I trigger based on time of passage in one scintillator counter used 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 were 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 Oct. 1989 to April 1991.

In the slow monopole search, 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]. No such events were found. For the data set of Spring 1989, a search requiring only single face trigger was also performed[16] and this method increased the acceptance by about a factor of 2.

The fast monopole search is performed on our

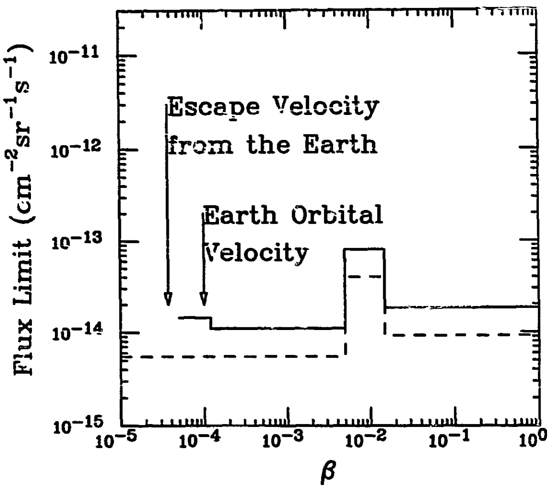

FIGURE 2
Nuclearite flux limit as a function of $\beta = v/c$ from the combined several MACRO searches. The solid line is for nuclearites heavier than 10^{-11}g but smaller than 0.1g (able to penetrate to the MACRO depth but not able to penetrate the whole Earth). The dashed line is for nuclearites that can penetrate the whole Earth (greater than 0.1g). The velocity coverage of MACRO detector includes the Earth orbital velocity around the Sun and extends to near the escape velocity from the Earth.

muon trigger data. In this search, we require consistency of streamer tube tracking and scintillator hits and then derive dE/dX in each scintillator counter after correcting for PMT saturation and light attenuation We then require that the particles penetrate at least two scintillator walls and have consistent dE/dX in each wall. No such events having dE/dX greater than 6 times that of an ordinary muon are found.

The combined flux limits from all these searches are shown in Fig.2, as a function of the nuclearite velocity. The MACRO search covers the velocity range from $\beta = 1$ down to $\beta = 5 \times 10^{-5}$, near the escape velocity of the earth. 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. Fig.3 shows the MACRO limit as a function of the nuclearites mass, together with the limits from other searches and the dark matter limit.

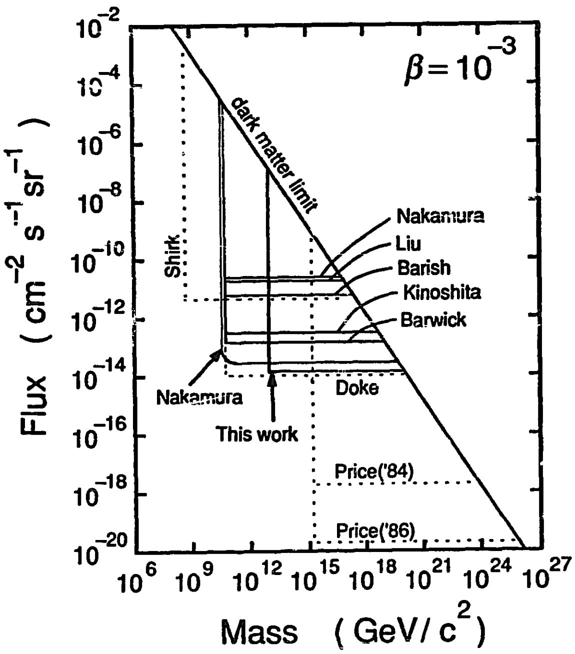

FIGURE 3
Compiled nuclearite flux limits as a function of the mass.

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