Search for Nuclearites Using the MACRO Detector

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(Received 8 June 1992)

A negative search using $\frac{1}{12}$ of the eventual MACRO detector has yielded nuclearite flux limits of 1.1×10^{-14} cm^{-2}sr^{-1}s^{-1} for $10^{-10} < m < 0.1$ g, and 5.5×10^{-15} cm^{-2}sr^{-1}s^{-1} for $m > 0.1$ g. We have modified the formula of De Rújula and Glashow for the light yield of nuclearites to include the uv light absorbed and reemitted in the visible region, and proved that the MACRO sensitivity extends almost to the escape velocity of the Earth. Our flux limit, therefore, can be used to address nuclearites that are possibly trapped in the solar system.

PACS numbers: 96.40.De, 14.80.Pb

It has been proposed that a new form of matter containing roughly equal numbers of up, down, and strange quarks might exist, be absolutely stable, and possibly be the true ground state of QCD for a given baryon number [1-5]. Within the range of presently allowed QCD parameters, such stable strange matter may have masses ranging from a few GeV to that of a neutron star. De Rújula and Glashow have suggested that strange matter might exist in the cosmic rays and they refer to such cosmic-ray strange matter as "nuclearites." Since the possible mass of nuclearites can be anywhere within such a wide region, searching for 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 nuclearites hitting the Earth [3,4]. Several cosmic-ray searches have been carried out at different altitudes and using different techniques. These include searches using scintillator detectors [6,7], ancient mica [8], plastic track-etch detectors [9-12], balloon-borne detectors [13], and a gravitational-wave detector [14].

MACRO (Monopole Astrophysics Cosmic Ray Observatory) is an underground detector situated at the Gran Sasso Laboratory in Italy at an average depth of 3700 meters of water equivalent (mwe) [15]. MACRO's primary physics goal is to search for heavy grand unified theory (GUT) magnetic monopoles, and the techniques developed for this purpose have been used to search for nuclearites that reach the MACRO depth.

The part of the MACRO detector used in this work is the first $\frac{1}{12}$ of the final MACRO detector. It consists of ten 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 dimensions of this detector are 12 m long, 11.3 m wide, and 4.5 m in height. A track-etch detector consisting of three layers of CR-39 is located horizontally in the middle of the apparatus.

We have employed two types of slow-particle triggers, which cover different β regions. The first trigger (type I) for the slowest particles ($\beta < 2.5\times10^{-3}$) is based on the time of passage of particles through a 19-cm-thick liquid scintillation counter. This trigger system recognizes wide pulses or long trains of single photoelectron pulses generated by slow particles, and rejects large and short pulses caused by muons and products of radioactive decay, the major sources of background. The second slow-particle trigger (type II) for an intermediate range ($2.5\times10^{-3} < \beta < 1.5\times10^{-2}$) is based on the time of flight between different walls of scintillators where the typical flight path is several meters. This system is simply a slow coincidence between walls vetoed by a fast coincidence between them. When either slow-particle trigger occurs, the wave forms of both the anode and the dynode for each photomultiplier tube (PMT) are recorded separately by two wave-form digitizers; each covers a different dynamical range.

In order to search for relativistic nuclearites ($1.5\times10^{-2} < \beta < 1$), we use our fast-particle (or muon) trigger data. When a muon trigger occurs, the pulse height and the time of each PMT signal are recorded by analog-to-digital and time-to-digital converters. Streamer-tube hits are also recorded and then used to reconstruct the tracks. Relativistic nuclearites can be recognized by their unusually high light yield.

De Rújula and Glashow have calculated the light yield of nuclearites traversing transparent materials based on the blackbody radiation of the heated track. The light yield per unit length of the track is given by [3] ($\hbar = c = 1$)

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

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 $\omega_{\max}$ is the maximum frequency for which the material is transparent. This formula assumes that only the blackbody radiation in the transparent region is collected.

In the scintillator, however, although it is not transparent in the uv region, the blackbody radiation emitted there is still collected through the wavelength shifters (which absorb uv and reemit it in the visible region). For this reason, $\omega_{\max}^{5/2}$ in Eq. (1) should be replaced by

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

where $\omega_{\max}^{0}$ is the maximum frequency for which the scintillator is transparent, N is the number of wave-shifter components, $\omega_{\max}^{ai}$ and $\omega_{\min}^{ai}$ are respectively the maximum and minimum absorption frequency of the 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 the transparent region). For the MACRO scintillator, expression (2) gives about $(4.35\text{ eV})^{5/2}$, which is about 2 times larger than the typical value for a transparent material.

Using Eq. (1) and replacing $\omega_{\max}^{5/2}$ by expression (2), we have calculated the light yield expected in a MACRO scintillator for nuclearites 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 derived from a direct measurement of the trigger circuit efficiency using simulated events produced by driving light-emitting diodes (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 1 order of magnitude, as shown in Fig. 1. The MACRO detector, with the special triggers described here, is sensitive to minimum size nuclearites ($m \leq 1.5$ ng) as slow as $5\times10^{-5}c$, close to the escape velocity of the Earth. The MACRO detector, therefore, is not only sensitive to nuclearites of galactic or extragalactic origin, but also sensitive to nuclearites that are possibly trapped in our solar system.

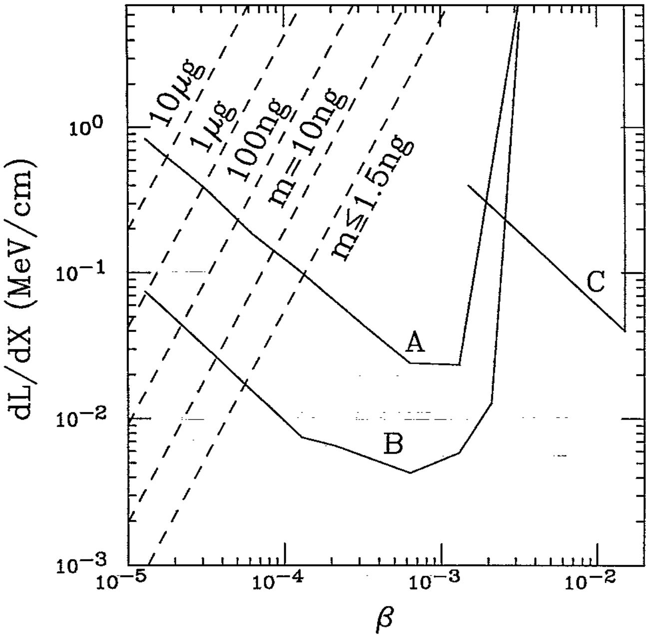

FIG. 1. Light yield of nuclearites in the MACRO scintillator as a function of velocity ($\beta=v/c$) for different masses of nuclearites (dashes). The solid curves are the 90%-trigger-efficiency contours of the MACRO slow-particle trigger system. Curve *A*: Type-I trigger based on time of passage in 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.

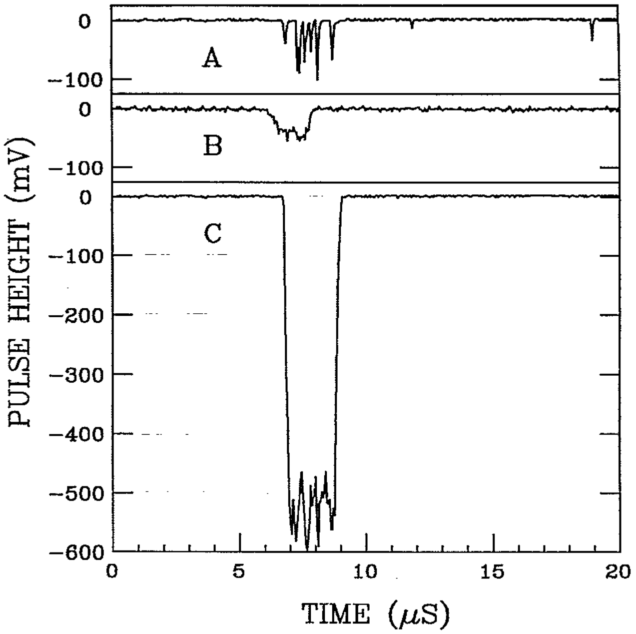

FIG. 2. Curve *A*: The wave form of the *best* slow-particle candidate. *B*: The wave form of an LED-simulated event having the same signal charge as *A*. *C*: A simulated wave form of a nuclearite with this pulse width ($\beta=3\times10^{-4}$). All the wave forms are drawn to the same scale.

The data sets used in this search consist of a 3-month run in spring 1989 and a run from October 1989 to April 1991. The geometric acceptance of the detector has been calculated using a Monte Carlo program. The live times and efficiencies were monitored by recording muons and other types of events.

For type-I trigger data, we acquired a total of 452 191 triggers during a live time of 3.96×10^7 sec in the run from October 1989 to April 1991. In the analysis we have required that the particle enter and exit the detector (at least two scintillator walls must have triggers), and this reduces the data sample to 392 events. Each of these events has been visually scanned to search for wide pulses or long pulse trains characteristic of a slow nuclearite passing through the detector [16]. Only two candidates were found, in which both triggering scintillator walls have pulse trains; however, neither has light levels and photoelectron fluctuations consistent with slow particles passing the detector. For the data set of spring 1989, a search requiring only a single-face trigger was also performed [17].

Figure 2 shows the wave form of the *best* slow-particle candidate found in the type-I trigger data. The candidate wave form *A* shows a pulse train, but it is too spiky to be consistent with a slow particle. This is illustrated in wave form *B* which was generated from an LED pulse of the same width and area. The LED-simulated event is much smoother and the small fluctuations are consistent with the photoelectron statistics. Furthermore, based on the length of the pulse train, the velocity is $\beta=3\times10^{-4}$, and such a nuclearite should give much more light and generate a wave form at least as large as *C*. For the two candidate events we also have checked the time of flight between the scintillator walls, and it is not consistent with the duration of the pulse train in each wall.

For type-II trigger data we visually scanned all 930 candidates in the data set of spring 1989. We found no candidate events. The triggers were all the result of electronic noise (637), cosmic-ray muons not rejected by the trigger (264), or muons that stop in the detector and subsequently decay, giving late signals (29).

Finally, the fast nuclearite search was performed using cosmic-ray muon trigger data to search for highly ionizing candidates. In this search, we required consistency between the streamer-tube track and scintillator hits and derived dL/dX in each scintillator counter after correcting for photomultiplier-tube nonlinearity and light attenuation. We found no event having a dL/dX in both walls greater than 10 times that of a muon. A fast nuclearite ($\beta>10^{-2}$), however, should have a dL/dX at least 3 orders of magnitude larger than that of a typical muon.

The combined flux limits (90% confidence level) from all these searches are shown in Fig. 3 as a function of the nuclearite velocity. They are down to 1.1×10^{-14}

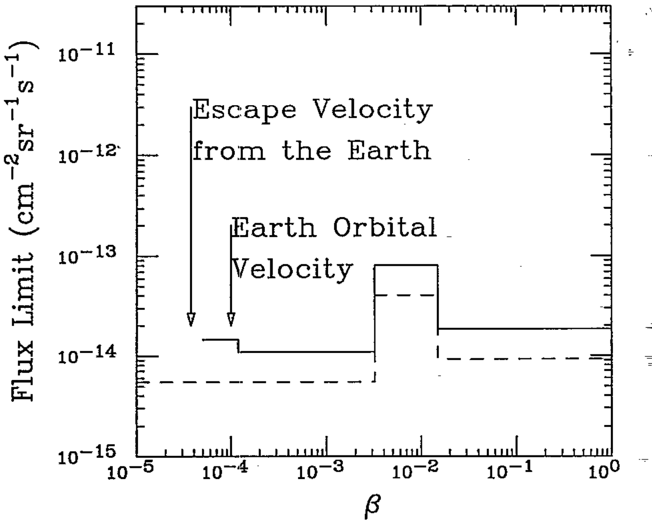

FIG. 3. Nuclearite flux limit as a function of $\beta = v/c$ from several MACRO searches combined (90% confidence level, based on zero observed events, derived from a maximum mean number of 2.3 events). Solid line (downward search only) is for nuclearites lighter than 0.1 g and therefore not having enough kinetic energy to come through the entire Earth. The dashed line (downward and upward search) is for nuclearites with enough kinetic energy to penetrate the Earth (greater than 0.1 g). The velocity coverage of the MACRO detector contains the Earth orbital velocity around the Sun and extends nearly to the escape velocity from the earth.

$\mathrm{cm^{-2}sr^{-1}s^{-1}}$ for nuclearites with mass $10^{-10} < m < 0.1$ g, and 5.5×10^{-15} $\mathrm{cm^{-2}sr^{-1}s^{-1}}$ for $m > 0.1$ g. These flux limits and velocity coverage may be compared with those obtained with plastic track-etch detectors. An experiment by Orito *et al.* using CR-39 has recently claimed the lowest flux limit for nuclearites over a wide β range. It should be pointed out that the vast majority of CR-39 calibrations are with fast ions ($\beta > 10^{-2}$). The only measurement so far for the low-β response of CR-39 comes from Snowden-Ifft and Price [18,19] showing a higher threshold for detection of slow ions compared to that of fast ones. Although this result is obtained with a specific type of CR-39, it raises a general question about the sensitivity of CR-39 in the low-β region and certainly suggests that at least a test of the CR-39 used by Orito *et al.* with low-β ions is needed in order to establish a definitive flux limit for nuclearites over the quoted β range. We calculated according to Ref. [15] that for minimum size nuclearites the β cutoff is at 1.7×10^{-4}. In addition, for very fast or large nuclearites, which deposit a tremendous amount of heat, the effect on the track-etch sensitivity is unclear. The same argument applies to other previous CR-39 experiments. The calculation of scintillator sensitivity we presented here is conservative and robust since it relies only on blackbody radiation and well-known scintillator properties. MACRO seems to be the only experiment to cover the entire β range from $\beta = 1$ down to the β range of nuclearites that are possibly trapped in our solar system.

We gratefully acknowledge Enric Bellotti (Director, LNGS), the Istituto Nazionale di Fisica Nucleare, the Laboratori Nazionali del Gran Sasso, the U.S. Department of Energy, the U.S. National Science Foundation, the North Atlantic Treaty Organization, and the Fulbright Foundation for their generous support of the MACRO experiment.

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