arXiv:hep-ex/9904031v1 28 Apr 1999

NUCLEARITE SEARCH WITH THE MACRO DETECTOR AT GRAN SASSO

The MACRO Collaboration

M. Ambrosio[12], R. Antolini[7], C. Aramo[7,n], G. Auriemma[14,a], A. Baldini[13], G. C. Barbarino[12], B. C. Barish[4], G. Battistoni[6,b], R. Bellotti[1], C. Bemporad[13], P. Bernardini[10], H. Bilokon[6], V. Bisi[16], C. Bloise[6], C. Bower[8], S. Bussino[18], F. Cafagna[1], M. Calicchio[1], D. Campana[12], M. Carboni[6], M. Castellano[1], S. Cecchini[2,c], F. Cei[11,13], V. Chiarella[6], B. C. Choudhary[4], S. Coutu[11,o], L. De Benedictis[1], G. De Cataldo[1], H. Dekhissi[2,17], C. De Marzo[1], I. De Mitri[9], J. Derkaoui[2,17], M. De Vincenzi[18], A. Di Credico[7], O. Erriquez[1], C. Favuzzi[1], C. Forti[6], P. Fusco[1], G. Giacomelli[2], G. Giannini[13,f], N. Giglietto[1], M. Giorgini[2], M. Grassi[13], L. Gray[4,7], A. Grillo[7], F. Guarino[12], P. Guarnaccia[1], C. Gustavino[7], A. Habig[3], K. Hanson[11], R. Heinz[8], Y. Huang[4], E. Iarocci[6,g], E. Katsavounidis[4], E. Kearns[3], H. Kim[4], S. Kyriazopoulou[4], E. Lamanna[14], C. Lane[5], T. Lari[7], D. S. Levin[11], P. Lipari[14], N. P. Longley[4,l], M. J. Longo[11], F. Maaroufi[2,17], G. Mancarella[10], G. Mandrioli[2], S. Manzoor[2,m], A. Margiotta[2], A. Marini[6], D. Martello[10], A. Marzari-Chiesa[16], M. N. Mazziotta[1], D. G. Michael[4], S. Mikheyev[4,7,h], L. Miller[8], P. Monacelli[9], T. Montaruli[1], M. Monteno[16], S. Mufson[8], J. Musser[8], D. Nicoló[13,d], C. Orth[3], G. Osteria[12], M. Ouchrif[2,17], O. Palamara[7], V. Patera[6,g], L. Patrizii[2], R. Pazzi[13], C. W. Peck[4], L. Perrone[10], S. Petrera[9], P. Pistilli[18], V. Popa[2,i], V. Pugliese[14], A. Rainò[1], A. Rastelli[7], J. Reynoldson[7], F. Ronga[6], U. Rubizzo[12], C. Satriano[14,a], L. Satta[6,g], E. Scapparone[7], K. Scholberg[3], A. Sciubba[6,g], P. Serra[2], M. Severi[14], M. Sioli[2], M. Sitta[16], P. Spinelli[1], M. Spinetti[6], M. Spurio[2], R. Steinberg[5], J. L. Stone[3], L. R. Sulak[3], A. Surdo[10], G. Tarlè[11], V. Togo[2], D. Ugolotti[2], M. Vakili[15], C. W. Walter[3], and R. Webb[15].

1. Dipartimento di Fisica dell'Università di Bari and INFN, 70126 Bari, Italy
2. Dipartimento di Fisica dell'Università di Bologna and INFN, 40126 Bologna, Italy

3. Physics Department, Boston University, Boston, MA 02215, USA
4. California Institute of Technology, Pasadena, CA 91125, USA
5. Department of Physics, Drexel University, Philadelphia, PA 19104, USA
6. Laboratori Nazionali di Frascati dell'INFN, 00044 Frascati (Roma), Italy
7. Laboratori Nazionali del Gran Sasso dell'INFN, 67010 Assergi (L'Aquila), Italy
8. Depts. of Physics and of Astronomy, Indiana University, Bloomington, IN 47405, USA
9. Dipartimento di Fisica dell'Università dell'Aquila and INFN, 67100 L'Aquila, Italy
10. Dipartimento di Fisica dell'Università di Lecce and INFN, 73100 Lecce, Italy
11. Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
12. Dipartimento di Fisica dell'Università di Napoli and INFN, 80125 Napoli, Italy
13. Dipartimento di Fisica dell'Università di Pisa and INFN, 56010 Pisa, Italy
14. Dipartimento di Fisica dell'Università di Roma "La Sapienza" and INFN, 00185 Roma, Italy
15. Physics Department, Texas A&M University, College Station, TX 77843, USA
16. Dipartimento di Fisica Sperimentale dell'Università di Torino and INFN, 10125 Torino, Italy
17. L.P.T.P., Faculty of Sciences, University Mohamed I, B.P. 524 Oujda, Morocco
18. Dipartimento di Fisica dell'Università di Roma Tre and INFN Sezione Roma III, Roma, Italy
a Also Università della Basilicata, 85100 Potenza, Italy
b Also INFN Milano, 20133 Milano, Italy
c Also Istituto TESRE/CNR, 40129 Bologna, Italy
d Also Scuola Normale Superiore di Pisa, 56010 Pisa, Italy
f Also Università di Trieste and INFN, 34100 Trieste, Italy
g Also Dipartimento di Energetica, Università di Roma, 00185 Roma, Italy
h Also Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia
i Also Institute for Space Sciences, 76900 Bucharest, Romania
l The Colorado College, Colorado Springs, CO 80903, USA
m RPD, PINSTECH, P.O. Nilore, Islamabad, Pakistan
n Also INFN Catania, 95129 Catania, Italy
o Also Department of Physics, Pennsylvania State University, University Park, PA 16801, USA

Submitted to The European Physical Journal C

Abstract

In this paper we present the results of a search for nuclearites in the penetrating cosmic radiation using the scintillator and track-etch subdetectors of the MACRO apparatus. The analyses cover the $\beta = v/c$ range at the detector depth (3700 hg/cm^2) $10^{-5} < \beta < 1$; for $\beta = 2 \times 10^{-3}$ the flux limit is $2.7 \times 10^{-16}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for an isotropic flux of nuclearites, and twice this value for a flux of downgoing nuclearites.

1 Introduction

In 1984 Witten formulated the hypothesis [1] that "strange quark matter" (SQM) composed of comparable amounts of u, d and s quarks might be the ground state of hadronic matter. "Bags" of SQM (also known as "strangelets") would be heavier than a single Λ^0 baryon, but neutral enough not to be limited in size by Coulomb repulsion.

If particles of SQM were produced in a first-order phase transition in the early universe, they would be candidates for Dark Matter (DM), and might be found in the cosmic radiation reaching the Earth. Particles of SQM in cosmic radiation are commonly known as "nuclearites" [2]. This paper describes an experimental search for nuclearites with the MACRO detector at Gran Sasso.

The main energy loss mechanism for nuclearites passing through matter is elastic or quasi-elastic atomic collisions [2]. The energy loss rate is

$$\frac{dE}{dx} = \sigma \rho v^2, \tag{1}$$

where σ is the nuclearite cross section, v its velocity and ρ the mass density of the traversed medium.

For nuclearites with masses $M \geq 8.4 \times 10^{14}$ GeV/c^2 ($\simeq 1.5$ ng) the cross section may be approximated as [2]:

$$\sigma \simeq \pi \times \left(\frac{3M}{4\pi\rho_N} \right)^{2/3} \tag{2}$$

where ρ_N (the density of strange quark matter) is estimated to be $\rho_N \simeq 3.5 \times 10^{14}$ g/cm^3, somewhat larger than that of atomic nuclei [3]. For nuclearites of masses

$M < 8.4 \times 10^{14}$ GeV/c^2 the collisions are governed by their electronic clouds, yielding $\sigma \simeq \pi \times 10^{-16}$ cm^2.

An experimental search for nuclearites has an acceptance that depends on nuclearite mass, since upgoing nuclearites that traverse the Earth before detection only occur for sufficiently large nuclearite masses ($\simeq 6 \times 10^{22}$ GeV/c^2 at typical galactic velocities [2]).

An upper limit on the nuclearite flux may be estimated assuming that $\Phi_{max.} = \rho_{DM} v/(2\pi M)$, where $\rho_{DM} \simeq 10^{-24}$ g/cm^3 represents the local DM density, and M and v are the mass and the velocity of nuclearites, respectively.

Different indirect methods to search for nuclearites have been suggested [2]. Some exotic cosmic ray events were interpreted as due to incident nuclearites, for example the "Centauro" events and particles with anomalous charge/mass ratio [4-10]. The interpretation of those possible signals is not yet clear. Searches for strangelets are being performed at the Brookhaven AGS [11] and at the CERN-SPS [12].

Relevant direct flux upper limits for nuclearites came from two large area experiments using CR39 nuclear track detectors; one experiment was performed at mountain altitude [13], the other at a depth of 10^4 g/cm^2 at the Ohya stone quarries [14].

The lowest flux limits have been obtained by examining ancient mica samples. It should be kept in mind however that this technique has inherent uncertainties [15, 16].

MACRO (Monopole, Astrophysics and Cosmic Ray Observatory) is an underground detector located at the Gran Sasso Laboratory in Italy, at an average depth of 3700 hg/cm^2 and at a minimum depth of 3150 hg/cm^2. MACRO uses three different types of detectors: liquid scintillators, limited streamer tubes and nuclear track detectors (CR39 and Lexan) arranged in a modular structure of six "supermodules" (SM's). The overall dimensions of the apparatus are $76.5 \times 12 \times 9.3$ m^3 [17]. The response of the three types of detectors to slow and fast particles has been experimentally studied [18-20]. One of the primary aims of MACRO is the search for superheavy GUT magnetic monopoles [21, 22]. Some of the search methods used for this purpose, namely those based on the liquid scintillators and nuclear track detectors, may also be applied to search for nuclearites.

In computing the acceptances for nuclearites of the scintillator and of the nuclear track subdetectors one has to take into consideration the nuclearite

absorption in the Earth. In Fig. 1 we present the fraction of solid angle from which nuclearites might reach MACRO as a function of their mass, assuming a velocity at the ground level of $\beta = 2\times10^{-3}$. For masses smaller than 5×10^{11} GeV/c^2 the nuclearites cannot reach the detector; for $5 \times 10^{12} \leq M \leq 10^{21}$ GeV/c^2 only downward going nuclearites can reach it; for $M > 10^{22}$ GeV/c^2 nuclearites from all directions can reach MACRO. The detector acceptance for an isotropic flux (at ground level) of nuclearites has to be scaled according to such curves.

Some earlier results obtained using the scintillator subsystem of the lower part of the first SM have been published [23]. More recent results obtained with the scintillator and CR39 subdetectors were reported in Ref. [24].

As recently suggested by Kusenko *et al.* [25], the MACRO search for nuclearites could also apply to Supersymmetric Electrically Charged Solitons (Q-balls, SECS). Q-balls are supersymmetric coherent states of squarks, sleptons and Higgs fields, predicted by minimal supersymmetric generalizations of the Standard Model [26]; they could be copiously produced in the early universe. Relic Q-balls are also candidates for cold DM [27].

In the following sections we present results on the search for nuclearites in the liquid scintillator and in the nuclear track subdetectors of MACRO. The density of the gas in the MACRO streamer tubes [19] is too low to allow the detection of nuclearites for the hypothesized energy loss mechanism.

2 Searches using the liquid scintillator subdetector

De Rújula and Glashow have calculated the light yield of nuclearites traversing transparent materials on the basis of the black-body radiation emitted along the heated track [2]. The light yield per unit track length is (in natural units, $\hbar = c = 1$)

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

where m is the mass of a molecule of the traversed material, n is the number of submolecular species in a molecule, ω_{max} is the maximum frequency for which the material is transparent, σ is the nuclearite cross section and v its velocity.

In Ref. [23] this formula was applied to our liquid scintillator. It was shown that the scintillator subdetector is sensitive even to very small nuclearite masses and to low velocities ($\beta \simeq 5\times10^{-5}$). The light yield is above the 90% trigger efficiency threshold of the MACRO scintillator slow-particle trigger system for most nuclearite masses ($dL/dX > 10^{-2}$ MeV cm^{-1}).

The scintillators are therefore sensitive not only to galactic ($\beta \sim 10^{-3}$) or extragalactic nuclearites (higher velocities), but also to those possibly trapped in our solar system ($\beta \sim 10^{-4}$).

The nuclearite detection efficiency in the scintillator subdetector is assumed to be similar (or larger) to that for magnetic monopoles; the selection criteria used to search for monopole events are also applicable for nuclearites. No saturation effects of the detectors, electronics, or reconstruction procedure are expected to reduce the detection efficiency of the liquid scintillator subdetector.

Different monopole triggers and analysis procedures have been used in the search for cosmic ray strangelets in different velocity domains following the evolution of the detector. The relevant parameters of each actual search for nuclearites using the scintillator subdetector are presented in Table 1. As no candidate satisfied all the requirements, the resulting flux upper limits at 90% confidence level (C.L.) are listed in Table 1 and presented in Fig. 2. Some details on the present searches are given below.

The slow monopole trigger which includes the analog Time Over Half Maximum (TOHM) electronics and the digital Leaky Integrator (LI) electronics [17, 22] recognizes wide pulses or long trains of single photoelectrons generated by slow particles, rejecting large and short pulses produced by muons or radioactive decay products. When a trigger occurs, the wave forms of both the anode and the dynode (for the 1989-91 run period) for each photomultiplier tube are separately recorded by two Wave Form Digitizers (WFD). A visual scan is then performed on the selected events. This procedure was applied to the searches for nuclearites with $10^{-5} < \beta < 3.5 \times 10^{-3}$ [23, 24].

The Fast Monopole Trigger (FMT) is based on the time of flight between two layers of scintillators. A slow coincidence between two layers is vetoed by a fast coincidence between them. Additional wave form analysis is performed on the selected events. This procedure was applied to the search for intermediate velocity nuclearites ($2.5 \times 10^{-3} < \beta < 1.5 \times 10^{-2}$) [23].

The scintillator muon trigger. A fast nuclearite should produce a light

yield (dL/dx) at least three orders of magnitude larger than that from a typical muon. It was checked that no negative effects arise on the detecting system from the larger pulse heights. No event was found having a dL/dx in both walls greater than 10 times that of a muon. This technique was applied in the early analyses for high velocity nuclearites ($1.5 \times 10^{-2} < \beta < 1$) [23].

The Energy Reconstruction Processor (ERP) is a single-counter energy threshold trigger [28, 29]. The ERP analysis requires triggers in two different scintillator planes, separated in the vertical direction by at least 2 m, insuring a time of flight long enough for accurate velocity measurements. The energy deposition must be at least 600 MeV in each counter. The ERP analysis was used to search for fast nuclearites ($\beta > 0.1$) [24]. The raw triggering efficiency for nuclearites with $\beta > 0.1$ is essentially 100%.

Pulse Height Recorder and Synchronous Encoder (PHRASE) is a system designed primarily for the detection of supernova neutrinos [28, 29]. The event selection requires a coincidence between two scintillator planes, with no more than 2 contiguous hits in each plane, with an energy release of at least 10 MeV in each layer. It was checked that no negative effects arise from larger pulse heights. A minimum separation of 2 m is required for hits in the two counters, while a software cut ($\beta \leq 0.1$) is imposed in order to reject the tail of the cosmic ray muon distribution. The particle velocity is reconstructed using the scintillator time information. The PHRASE search for nuclearites covers a large velocity range: $1.2 \times 10^{-3} < \beta < 10^{-1}$ [24]. The lower limit corresponds to the threshold for the detection of bare monopoles with unit Dirac magnetic charge ($g = g_D$); as the light yield produced by nuclearites is larger than that of monopoles, the nuclearite search might be extended to lower velocities. For candidates with $\beta \leq 5 \times 10^{-3}$ we compare the duration of the scintillation light pulse (measured by the PHRASE WFD) with the one computed using the particle velocity; candidates with $5 \times 10^{-3} \leq \beta < 0.1$ are cross-checked on the basis of the measured energy loss. All the candidates with $\beta \simeq 5 \times 10^{-3}$ are examined using both techniques, in order to ensure the continuity of the analysis.

3 Searches using the nuclear track subdetector

The nuclear track detector is located horizontally in the middle of the lower MACRO structure, on the vertical east wall and on the lower part of the vertical north wall. It is organised in modules ("wagons") of $\sim 25 \times 25\,\mathrm{cm}^2$; a "wagon" contains three layers of CR39, three layers of lexan and 1 mm thick aluminium absorber. Details of the track-etch subdetector are given in Ref. [30]; the total area is 1263 m^2. At the point that this analysis ended we had etched 227 m^2 of CR39 with an average exposure time of 7.6 years. In Ref. [20] it was shown that the formation of an etchable track in CR39 is related to the Restricted Energy Loss (REL) which is the fraction of the total energy loss which remains localized in a cylindrical region with about 10 nm diameter around the particle trajectory [31]. There are two contributions to REL: the electronic energy loss (S_e), which represents the energy transferred to the electrons, and the nuclear energy loss (S_n), which represents the energy transferred to the nuclei in the material. In Ref. [20] it was shown that S_n is as effective as S_e in producing etchable tracks in our CR39. This result was confirmed in Ref. [32] for different types of CR39. In the case of nuclearites the REL is practically equal to S_n; thus Eq. 1 may be used for calculating REL.

In Fig. 3 we present the energy loss of nuclearites in CR39; the calculation assumes that the energy is transferred to the traversed material by displacing the matter in the nuclearite path by elastic or quasi-elastic collisions. Such processes would produce the breaking of the CR39 polymeric bonds, leaving etchable latent tracks, if the energy loss is above the detector threshold. For the MACRO CR39 the "intrinsic" threshold is about 20 MeV $\mathrm{g}^{-1}\mathrm{cm}^2$ in the condition of a chemical etching in 8N NaOH water solution at 80° C; this is shown in Fig. 3 as the lower horizontal line. The dotted line in Fig. 3 represents the REL for $g = g_D$ bare magnetic monopoles in CR39 [33].

Several "tracks" were observed, mainly due to recoil protons from neutron interactions or due to polymerization inhomogeneities. In the conditions of the average exposure time in MACRO the number of background tracks is about 0.5 $/\mathrm{m}^2$ of CR39. When we required that the observed etch cones were present on at least four CR39 surfaces and were consistent with being from the same particle track, all of the candidates were ruled out.

From Fig. 3 it is apparent that our CR39 is sensitive to nuclearites of any mass and with $\beta > 1.5 \times 10^{-5}$. Nuclearites with mass larger than $\sim 10^{15}$ GeV/c^2 can be detected even for velocities as small as $\beta = 10^{-5}$. As a consequence, the 90% C.L. limit for $\beta \sim 1$ monopoles established by the nuclear track subdetector (6.8×10^{-16} cm^{-2}s^{-1}sr^{-1}) applies also to an isotropic flux of $M > 5.6 \times 10^{22}$ GeV/c^2 nuclearites. This limit is presented in Fig. 2 as curve "F" and is included in Table 1. For lower mass nuclearites the 90% C.L. flux limit is twice this value (1.4×10^{-15} cm^{-2}s^{-1}sr^{-1}) because of the solid angle effect shown in Fig. 1.

4 Discussions and conclusions

No nuclearite candidate was found in any of the reported searches. The 90% C.L. flux upper limits for an isotropic flux of nuclearites are presented in Fig. 2.

Because either the scintillator or the CR39 can give us a credible nuclearite detection, we sum the independent parts of the individual exposures to obtain the global limit denoted as "MACRO" in Fig. 2. This procedure ensures the 90% C.L. significance of the global limit.

All limits presented in Fig. 2 refer to the flux of nuclearites at the level of the MACRO detector, i.e., below an average rock thickness of 3700 hg/cm^2. To compare our limit with the limits published by different experiments and with the limit calculated from DM density in our galaxy, we integrated the energy loss equation for a path corresponding to the averaged rock thickness and for different velocities at the detection level. Thus we obtained a relation between the nuclearite velocities at the level of the detector and at the ground level. Similar calculations were made for other underground experiments [14, 15].

Fig. 4 shows the 90% C.L. MACRO upper limit for a flux of downgoing nuclearites compared with the limits reported in Refs. [13] ("Nakamura"), [14] ("Orito"), the indirect mica limits [15, 16] and with the DM limit, assuming a velocity at ground level of $\beta = 2 \times 10^{-3}$. At $\beta = 2 \times 10^{-3}$ the 90% C.L. MACRO limit for an isotropic flux of nuclearites is 2.7×10^{-16} cm^{-2}s^{-1}sr^{-1}. In Fig. 4 we extended the MACRO limit above the DM bound, in order to show the transition to an isotropic flux for nuclearite masses larger than $\simeq 6 \times 10^{22}$ GeV/c^2.

Acknowledgements.

We gratefully acknowledge the support of the director and of the staff of the Laboratori Nazionali del Gran Sasso and the invaluable assistance of the technical staff of the Institutions participating in the experiment. We thank the Istituto Nazionale di Fisica Nucleare (INFN), the U.S. Department of Energy and the U.S. National Science Foundation for their generous support of the MACRO experiment. We thank INFN, ICTP (Trieste) and World Laboratory for providing fellowships and grants for non Italian citizens.

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Label in Fig. 2	Method	SM's	β range	Run period	Live time (days)	Isotropic 90% C.L. flux limit ($cm^{-2}\,s^{-1}\,sr^{-1}$)	Ref.
A	TOHM FMT μ-trigger	1	10^{-5} – 2.5×10^{-3} 2.5×10^{-3}–1.5×10^{-2} 1.5×10^{-2}– 1	3/89–4/91	457.5	5.5×10^{-15} 4.0×10^{-14} 9.0×10^{-15}	[23]
B	TOHM	1	10^{-5} – 3.5×10^{-3}	10/89–11/91	453	5.6×10^{-15}	[24]
C	TOHM	1–6	10^{-5} – 10^{-2}	12/92–6/93	163.5	4.1×10^{-15}	[24]
D	ERP	1–6	0.1 – 1	12/92–6/93	166.5	4.4×10^{-15}	[24]
E	PHRASE	various	1.2×10^{-3}– 0.1	10/89–12/98	2587.5	3.6×10^{-16}	[24]*
F	CR39	1–3	10^{-5} – 1	9/88–3/99	-†	6.8×10^{-16}	[24]*

* Analyses updated in this paper.

†For the CR39 it is more appropriate to quote the average exposure time of the etched part (7.57 years).

Table 1. Summary of the nuclearite searches with the scintillator and with the CR39 subdetectors. The different techniques are briefly explained in the text. Further details are given in the quoted references. At $\beta = 2\times10^{-3}$ the combined MACRO limit is 2.7×10^{-16} $cm^{-2}s^{-1}sr^{-1}$. (The procedure to obtain the MACRO limit takes care of the overlapping in beta and time ranges of individual analyses).

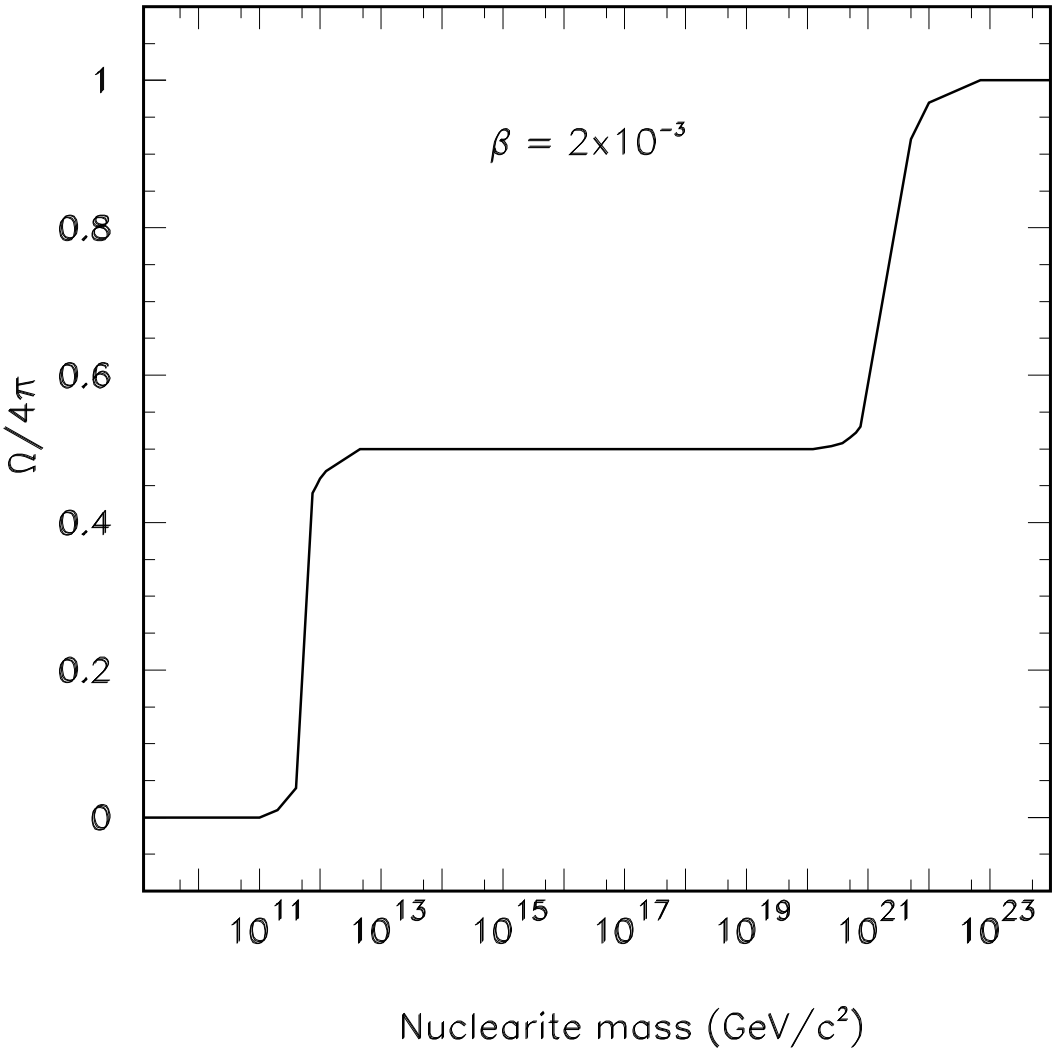

Figure 1: Fraction of the solid angle from which nuclearites with $\beta = 2 \times 10^{-3}$ and different masses might reach the MACRO detector. For masses smaller than 5×10^{11} GeV/c^2 the nuclearites cannot reach the detector; for $10^{12} \leq M \leq 10^{21}$ GeV/c^2 only downward going nuclearites can reach it; for $M > 10^{22}$ GeV/c^2 nuclearites from all directions can reach MACRO.

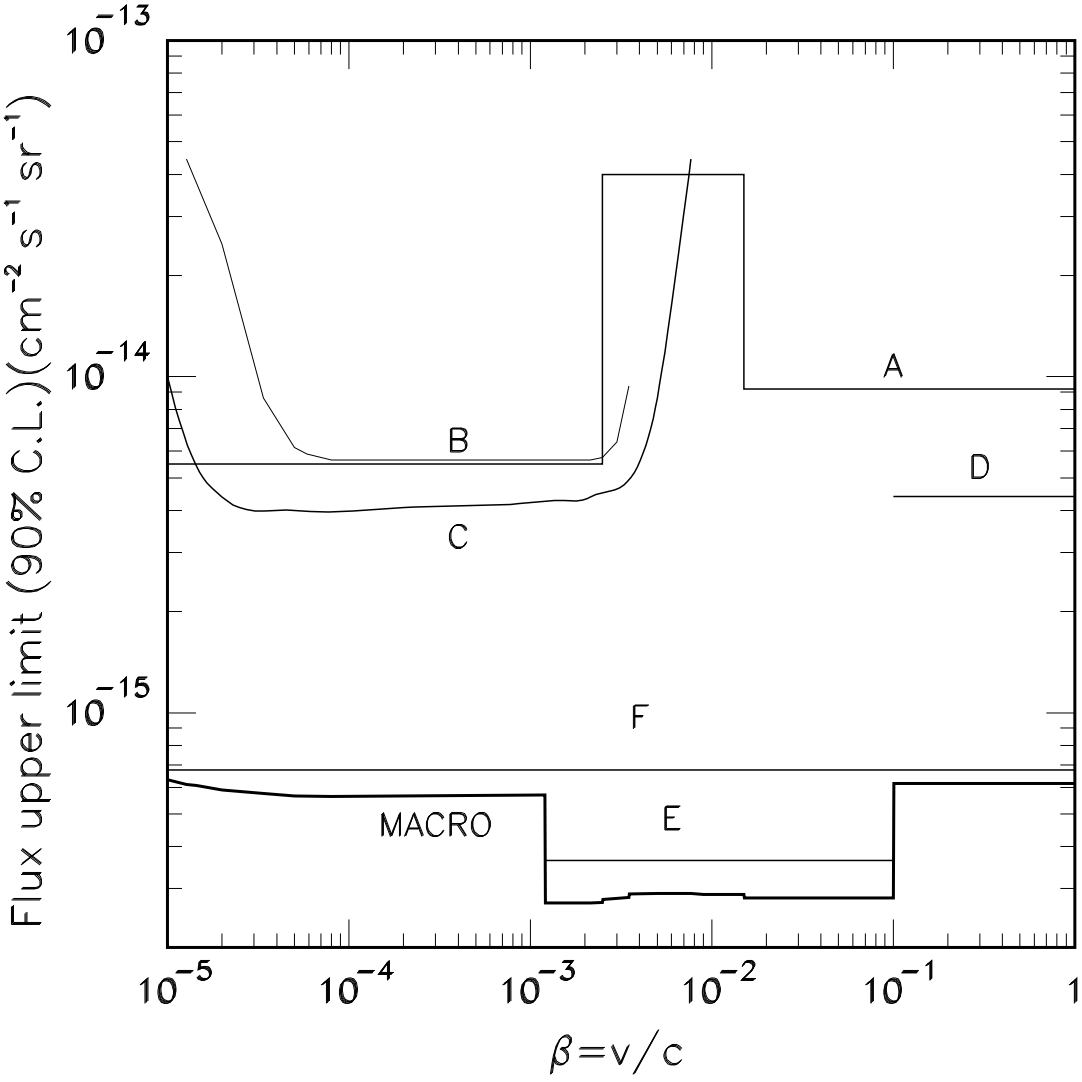

Figure 2: The 90% C.L. upper limits for an isotropic flux of nuclearites obtained using the liquid scintillator (curves A - E) and the CR39 nuclear track (curve F) subdetectors; the bold line is the present MACRO global limit.

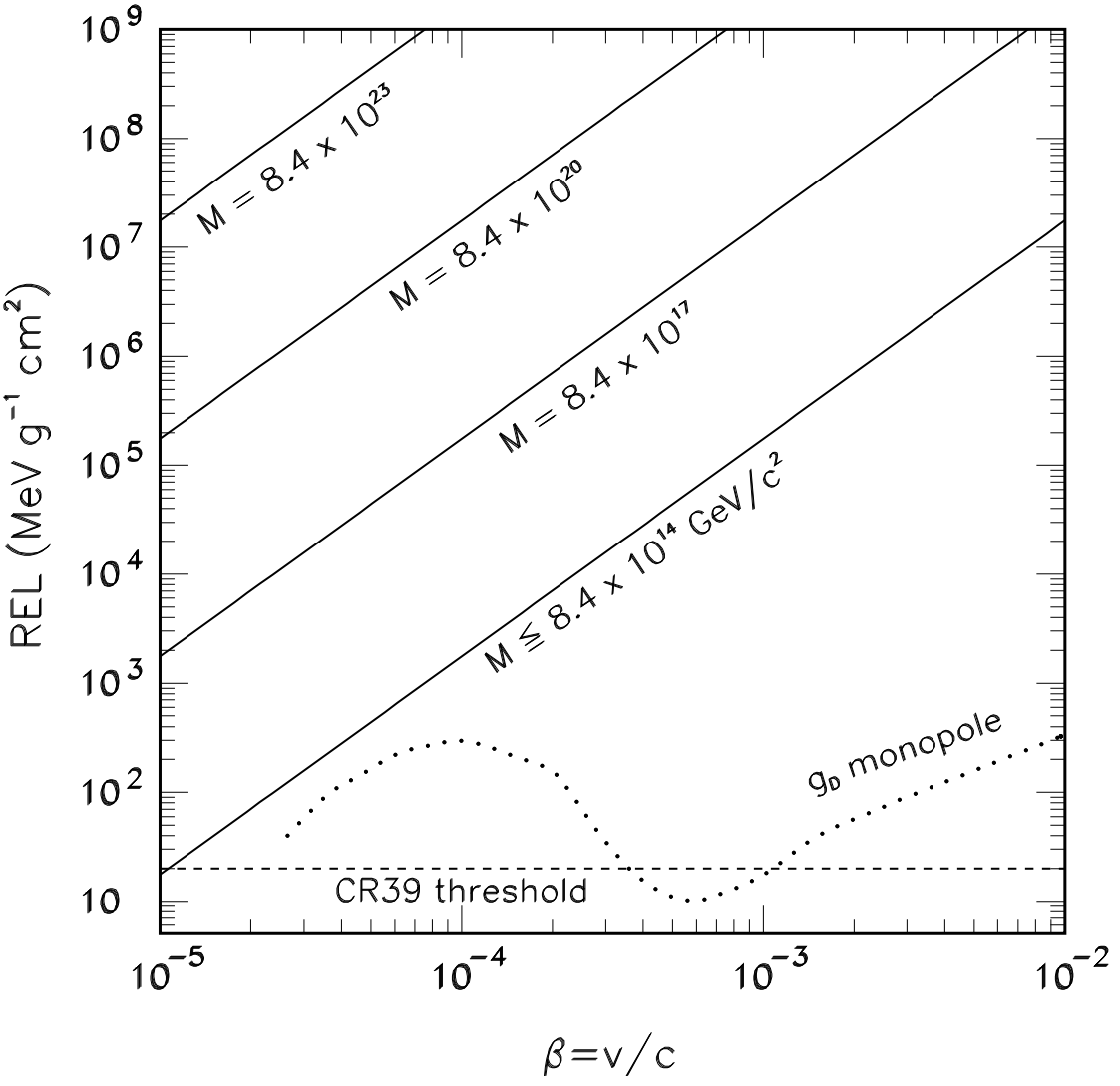

Figure 3: Restricted energy losses in CR39 for nuclearites of different velocities and masses M (in GeV/c^2). The dotted line shows the REL of magnetic monopoles with unit Dirac magnetic charge ($g = g_D$) in CR39 and is included for comparison. The threshold of our CR39 is also presented.

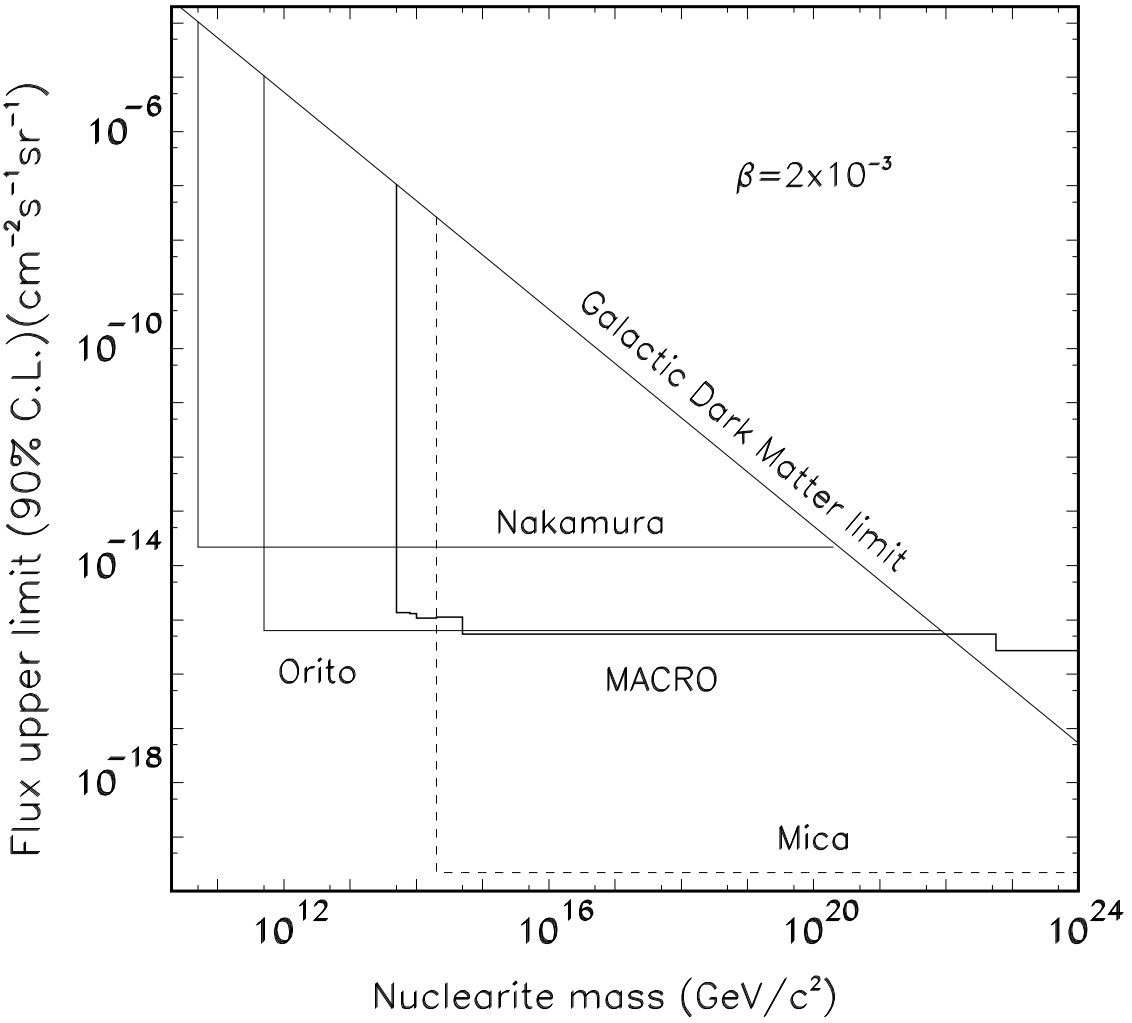

Figure 4: 90% C.L. flux upper limits versus mass for downgoing nuclearites with $\beta = 2 \times 10^{-3}$ at ground level. Nuclearites of such velocity could have galactic or extragalactic origin. The MACRO direct limit is shown along with the limits from Refs. [13] ("Nakamura"), [14] ("Orito") and the indirect mica limits of Refs. [15,16] (dashed line). The MACRO limit for nuclearite masses larger than 5×10^{22} GeV/c^2 has been extended and corresponds to an isotropic flux.