BRIEF REPORTS

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Upper limit for nuclearite flux from the Rome gravitational wave resonant detectors

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Flux limits for nuclearites at sea level are given, making use of the resonant gravitational wave detector Explorer. It is found, at the 90% confidence level, that there are less than 1.8×10^{-12} cm^{-2} sr^{-1} s^{-1} with β ranging from 1 to 0.001.

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Witten proposed in 1984 [1] that a new form of matter, consisting of aggregates of up, down, and strange quarks in roughly the same proportion, might exist and be stable. These particles, called "nuclearites," may have masses ranging from a few GeV to the mass of a neutron star.

In 1988 Liu and Barish showed [2] that resonant-bar gravitational wave detectors are sensitive to nuclearites and obtained a flux limit from the data of a 252 h run of the Stanford detector. We have applied the same procedure to the data of the Explorer detector, recorded during the period June–December 1991 for a total time of 133.8 days. We present the upper limit for the flux of nuclearites obtained with these data.

The principal energy-loss mechanism for a nuclearite passing through matter is via atomic collisions. According to Refs. [2–4] when a nuclearite of mass m and velocity βc goes through an aluminum body, the rate of energy loss is

$$\frac{dE}{dx}=480\frac{\mathrm{GeV}}{\mathrm{cm}}\left[\frac{\beta\theta(m)}{10^{-3}}\right]^2 ,$$

where the mass dependence is

$$\theta(m)=1 \quad \text{if } m\le 1.5 \text{ ng} ,$$

$$\theta(m)=\left[\frac{m}{1.5\text{ ng}}\right]^{1/3} \quad \text{if } m\ge 1.5 \text{ ng} .$$

Present resonant-mass gravitational radiation detectors consist of a solid cylinder of aluminum, with the fundamental resonance near 1 kHz. The excitation of the cylinder fundamental mode due to a high-energy particle has been discussed by many authors [2,3,5–8].

It is customary to describe the sensitivity for the mode energy variations of a gravitational wave antenna by means of a "detection effective temperature"

$$\Delta T=\varepsilon/k .$$

According to Liu and Barish [2] the energy deposited in the fundamental mode by a particle crossing the bar is given by

$$\Delta T=\frac{\varepsilon}{k}=\frac{\varepsilon_0}{k}\left[\sin\frac{\pi z_0}{L}\right]^2\left[\frac{\sin(\pi l_0\cos(\theta_0)/2L)}{\pi R\cos(\theta_0)/L}\right]^2 ,$$

where

$$\varepsilon_0=\frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}\left[\frac{dE}{dx}\right]^2 ,$$

L is the bar length, R the bar radius, v the sound velocity in the bar material ($v=5400$ m/s at low temperatures), e the density of aluminum, γ the ratio of the thermal expansion coefficient to the specific heat which, according to the Gruneisen law, is slowly changing with temperature ($\gamma=1.6$ in aluminum at low temperatures), l_0 the length of the particle's track inside the bar, z_0 the distance of the track midpoint from one end of the bar, and θ_0 the angle between the particle track and the axis of the bar (see Fig. 1).

The detector [9] consists of a resonant bar equipped

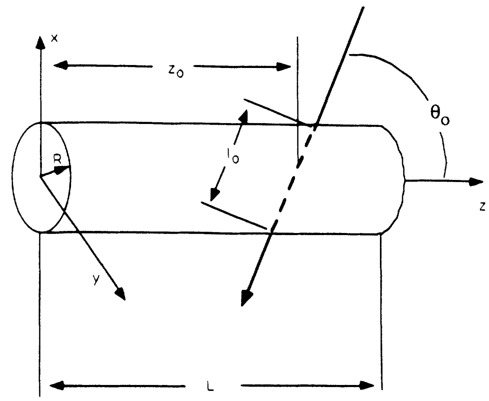

FIG. 1. Definition of the geometrical parameters.

with a resonant capacitive transducer and a dc superconducting quantum interference device (SQUID) amplifier. The bar is a cylinder of 0.6 m diam and 2.97 m length, made of Al 5056. Its resonance frequency (first longitudinal mode) is 915.69 Hz at liquid helium temperature.

For this detector we have

$$\Delta T = \frac{\varepsilon_0}{k} = 6.56 \left[\frac{\beta\theta(m)}{10^{-3}} \right]^4 \text{ K} .$$

This is a factor of 2 smaller than that given in Ref. [2], because here we use numerical values at low temperatures.

The detector acceptance is defined as the ratio of the rate of events detected by the antenna to the flux of incident particles. Therefore, the acceptance depends on the geometric cross section and on the capability of a given incident particle to produce an event above the chosen threshold.

The geometric cross section of the bar is $S = 1.8$ m^2, and then the maximum value of the acceptance for an isotropic flux of particles can be simply expressed as

$$A = S4\pi = 22.6 \text{ m}^2\text{sr} .$$

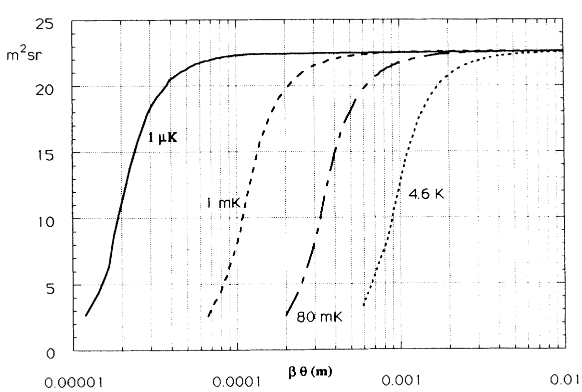

FIG. 2. Acceptance of the gravitational wave detector at the energy thresholds $\Delta T = 1$ μK, 1 mK, 0.08 K, and 4.6 K. The vertical axis has to be divided by 2 if $m < 0.1$ g (nuclearites that cannot penetrate the Earth).

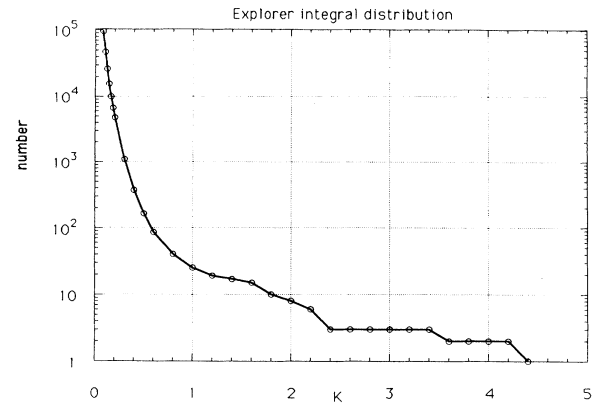

FIG. 3. Integral distribution of the Explorer events (peak values above 80 mK) during the period 2 June–16 December 1991 (total observation time of 133.8 days).

We have obtained the acceptance of the Explorer detector for an isotropic flux of nuclearites at various ΔT values, by means of a Monte Carlo procedure, taking into account the energy and trajectory inside the antenna of the incident particles.

If a nuclearite with given mass and velocity β crosses the bar, the amount of energy deposited in the bar at its resonance mode, or, equivalently, the ΔT, is a function of the parameters l_0, z_0, θ_0. The results are shown in Fig. 2, for different ΔT values. The acceptance reaches its maximum value for different β of the nuclearite, as a function of the different energy thresholds. The β value at which the acceptance reduces to 0.85 of the maximum is called the β cutoff because, for β less than the β cutoff, the acceptance of the detector decreases very quickly. For $\Delta T = 4.6$ K, the energy used for the Stanford detector, the acceptance reduces to 0.85 of the maximum value at $\beta = 0.0013$.

The present sensitivity of the Explorer detector is such

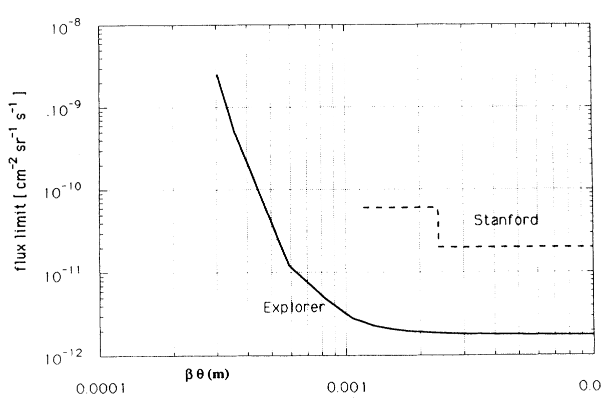

FIG. 4. Flux limit obtained with the data of 133.8 days of the Explorer detector, compared with the Stanford flux limit (10.5 days, 1980). This limit applies to nuclearites that can penetrate the atmosphere, i.e., with mass greater than 1.5×10^{-13} g. For nuclearites that can penetrate the Earth (heavier than 0.1 g) the limit is a factor 2 lower.

TABLE I. Upper limits for nuclearites.

Experiment (m in grams)	Year	Detector	β range a	Flux limit ($\mathrm{cm^2 sr^{-1} s^{-1}}$)
Skylab	Shrink-Price	Array of	0.05[b]	3.0×10^{-12}
$m>4\times10^{-17}$	1978	Lexan det.		
Mountain	Barwick	Plastic track	0.012[b]	2.9×10^{-13}
$m>3\times10^{-14}$	1983	CR-89	1	
Sea level	Doke	Plastic track	0.04[b]	5.0×10^{-15}
$m>1.5\times10^{-13}$	1983		1	
Sea level	Nakamura	Scintillator	10^{-4}	3.2×10^{-11}
$m>1.5\times10^{-13}$	1985		10^{-3}	
Sea level	Barish		3×10^{-4}	4.0×10^{-12}
$m>1.5\times10^{-13}$	1987		7×10^{-3}	
Sea level	Liu-Barish	Aluminum	10^{-3}	2.0×10^{-11}
$m>1.5\times10^{-13}$	1988	bar	1	
Sea level	Explorer	Aluminum	1×10^{-3}	1.8×10^{-12}
$m>1.5\times10^{-13}$	1991	bar	1	
Undergr.	Price	Mica	3×10^{-5}	1×10^{-20}
$m>2.4\times10^{-10}$	1986		0.05	
Undergr.	Orito *et al.*	Plastic track	4×10^{-5}	3.2×10^{-16}
$m>1.8\times10^{-12}$	1991	CR-89	1	
Undergr.	Macro	Scintillators	5×10^{-5}	1.1×10^{-14}
$m>1.0\times10^{-11}$	1992		1	

[a]The β range estimation in plastic detectors is rough, because the actual energy loss in these detectors is still being debated.
[b]This estimation is valid for monopoles, since the original papers did not provide the range for the nuclearites.

that we must use, in our computations, the acceptance functions at an energy greater or equal to $\Delta T=80$ mK since the Explorer events are defined as those signals exceeding the threshold of 80 mK, that is, eight times the average noise level [8]. In Fig. 2 we show the acceptance functions also for the thresholds $\Delta T=1$ μK and 1 mK that we plan to reach with the more sensitive ultracryogenic Nautilus [10] detector. At these two thresholds the β cutoffs are reduced, respectively, to 2.0×10^{-4} and 3.0×10^{-5}.

For determining the upper limit for the flux of nuclearites on Earth at the Geneva altitude, near sea level, we have used the data of the Explorer detector taken during the period 2 June 1991 to 16 December 1991 [9]. The total observation time is 133.8 days. The integral distribution of the events with peak values above 80 mK is shown in Fig. 3. In the statistical analysis we have assumed a confidence level of 90%. The flux limit (expressed as $\mathrm{m^{-2}sr^{-1}s^{-1}}$) has been evaluated from the events distribution and the acceptance functions by evaluating, at different energy thresholds,

$$F(\Delta T)=\frac{N(\Delta T)(90\%\ \mathrm{C.L.})}{[\mathrm{acceptance}(\Delta T)\times\mathrm{time\ of\ observation}]}$$

and then by choosing the minimum of the corresponding $F(\Delta T)$ values.

The results are plotted in Fig. 4, where, for comparison, the flux limit obtained [2] with the Stanford detector during a 252 h run in 1980 is also reported. In the region of $\beta\geq10^{-3}$ we have improved the previous upper limit by over one order of magnitude.

Several other groups [11], with various techniques, have obtained the upper limit flux for nuclearites. We show their results, very schematically, in Table I. If we compare, for instance, our results with those obtained in 1991 with the Macro Detector [12,13], we note that the Macro flux limit is about two orders of magnitude lower than ours. However, since Macro is an underground detector, located in the Gran Sasso laboratory at a minimum depth of 3400 meters of water equivalent, this flux limit applies only to nuclearites able to penetrate down to the Macro depth, i.e., with a mass greater than 10^{-11} g.

In our case (at the sea level) the flux limit applies to nuclearites with smaller mass (down to 1.5×10^{-13} g). Thus our result gives new information on the search for nuclearites, by extending the results obtained with the underground experiments to a lower range of nuclearite mass and providing, comparing with the other ones at sea level, a wider β range. It is also interesting to note that our flux limit has been obtained (unlike the Macro detector) by acoustic and mechanical detection techniques. As already pointed out by Liu and Barish this is a new technique for particle detection.

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[1] E. Witten, Phys. Rev. D **30**, 272 (1984).
[2] G. Liu and B. Barish, Phys. Rev. Lett. **61**, 271 (1988).
[3] C. Bernard, A. De Rújula, and B. Lautrup, Nucl. Phys. **B242**, 93 (1984).
[4] A. De Rújula and S. L. Glashow, Nature (London) **312**, 734 (1984).
[5] A. M. Grassi Strini, G. Strini, and G. Tagliaferri, J. Appl. Phys. **51**, 849 (1980).
[6] E. Amaldi and G. Pizzella, Nuovo Cimento **9C**, 612 (1986).
[7] J. Chiang, P. Michelson, and J. Price, Nucl. Instrum. Methods A **311**, 603 (1992).
[8] A. M. Allega and N. Cabibbo, Lett. Nuovo Cimento **38**, 263 (1983).
[9] P. Astone, M. Bassan, P. Bonifazi, P. Carelli, M. G. Castellano, G. Cavallari, E. Coccia, C. Cosmelli, V. Fafone, S. Frasca, E. Majorana, I. Modena, G. V. Pallottino, G. Pizzella, P. Rapagnani, F. Ricci, and M. Visco, Phys. Rev. D **47**, 362 (1993).
[10] P. Astone, M. Bassan, P. Bonifazi, E. Coccia, C. Cosmelli, V. Fafone, S. Frasca, E. Majorana, I. Modena, G. V. Pallottino, G. Pizzella, P. Rapagnani, F. Ricci, and M. Visco, Europhys. Lett. **16**, 231 (1991).
[11] P. B. Price, Phys. Rev. D **38**, 3813 (1988).
[12] MACRO Collaboration, in *Strange Quark Matter in Physics and Astrophysics,* Proceedings of the International Workshop, Aarhus, Denmark, 1991, edited by J. Madsen and P. Haensel [Nucl. Phys. B (Proc. Suppl.) **24B**, 191 (1991)].
[13] MACRO Collaboration, S. Ahlen *et al.*, Phys. Rev. Lett. **69**, 1860 (1992).