# Nuclearite Flux Limit from Gravitational-Wave Detectors

G. Liu and B. Barish
*California Institute of Technology, Pasadena, California 91125*
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It is shown that present-day resonant-bar gravitational-wave detectors are sensitive to nuclearites of strange matter. The published data from a short test run of the Stanford gravitational-wave detector are used to obtain a flux limit for nuclearites.

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It has been pointed out that,[1,2] when the noise temperature of resonant-bar gravitational-wave detectors are reduced below $10^{-5}$ K, they will be sensitive to cosmic-ray magnetic monopoles. Recently, another possibility of slow-moving cosmic-ray particles, called "strange matter" or "nuclearites," has been proposed.[3-6] Such a particle consists of up, down, and strange quarks, may be absolutely stable, and may have a mass ranging from a few gigaelectronvolts to the mass of a neutron star. Nuclearites are an attractive candidate for the dark matter, since they depend only on certain effects of QCD, which, unlike the theories of many other candidates, is firmly supported by experiments. According to Eqs. (2) and (4) of Ref. 5, a nuclearite of mass $m$ traversing aluminum with velocity $\beta c$ has energy loss

$$\left(\frac{dE}{dX}\right) \sim (480\ \mathrm{GeV/cm}) \left(\frac{\beta}{10^{-3}}\right)^2 \times \begin{cases} 1, & m < 1.5\ \mathrm{ng}, \\ [m/(1.5\ \mathrm{ng})]^{2/3}, & m > 1.5\ \mathrm{ng}. \end{cases} \tag{1}$$

This energy loss is about 1000 times more than that of a magnetic monopole and could be detectable in the present generation of resonant-bar gravitational-wave detectors.

A particle with energy loss $(dE/dX)$ crossing the resonant bar would cause the oscillation energy of $n$th normal mode to rise by an amount[7]

$$\delta E_n = [2M\omega_n^2(1-2\sigma)^2]^{-1}(\alpha Y/C_p)^2(dE/dX)^2\left(\int \mathrm{div}\,\mathbf{u}_n(\mathbf{x})\,dl\right)^2, \tag{2}$$

where $M$ is the total mass of the bar, $\omega_n$ is the angular frequency of the $n$th normal mode, $\sigma$ is Poisson's ratio, $\alpha$ is the linear thermal expansion coefficient, $Y$ is the Young's modulus, $C_p$ is the specific heat, $\mathbf{u}_n(\mathbf{x})$ is the spatial part of the $n$th normal-mode oscillation normalized to the volume of the bar (see Refs. 2 and 7), and the integral is a line integral along the particle's track inside the bar. Equation (2) is a general formula; it applies to all resonant detectors with arbitrary shape.

For the axially symmetric normal modes of a long resonant bar of length $L$ and radius $R$ ($R \ll L$), $\mathbf{u}_n(\mathbf{x})$ and $\omega_n^2$ can be approximately written as[8]

$$\begin{aligned} u_n^r(r,z) &= \sqrt{2}\sigma n\pi(r/L)\sin(n\pi z/L) + O((R/L)^3), \\ u_n^z(r,z) &= \sqrt{2}\cos(n\pi z/L) + O((R/L)^2), \\ \omega_n^2 &= (n\pi/L)^2(Y/\rho)[1+O((R/L)^2)]. \end{aligned} \tag{3}$$

If we use Eqs. (2) and (3) and ignore all $(R/L)^2$ and higher-order terms, the oscillation energy caused by a crossing particle is calculated to be, when expressed conventionally as the "temperature,"

$$\delta T \equiv \frac{\delta E_n}{k} = \delta T_0 \left[\sin\frac{n\pi z_0}{L}\,\frac{\sin(n\pi l_0\cos\theta/2L)}{n\pi R\cos\theta/L}\right]^2, \tag{4}$$

where

$$\delta T_0 = \frac{1}{k}\left(\frac{2\pi R}{L}\right)^2\left(\frac{\alpha Y}{C_p}\right)^2\frac{1}{M\omega_1^2}\left(\frac{dE}{dX}\right)^2, \tag{5}$$

$k$ is the Boltzmann constant, $l_0$ is the length of the particle's track inside the bar, $z_0$ is the distance of the track's midpoint from one end of the bar, and $\theta$ is the angle between the particle's track and the axis of the bar (Fig. 1). Equation (4) is fairly accurate, since the terms ignored are only order of $(R/L)^2$. Normally, this does not exceed a few percent.

In particular, for the Stanford gravitational-wave detector,[9]

$$\delta T_0 = (13.2\ \mathrm{K}) \left( \frac{\beta}{10^{-3}} \right)^4 \times \begin{cases} 1, & m < 1.5\ \mathrm{ng}, \\ [m/(1.5\ \mathrm{ng})]^{4/3}, & m > 1.5\ \mathrm{ng}. \end{cases} \quad (6)$$

Typically, such a signal is sizable compared with the background noise.

In a 252-h test run of the Stanford gravitational-wave detector,[9] only three events over 0.4 K were observed and none was above 15 K. By approximately treating the end effects, we determined the acceptance of the detector to be 25.5 $\mathrm{m}^2$ sr for an isotropic flux. From this, we obtain a flux limit of $2.9 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$ [90% confidence level (C.L.)] for the nuclearites that can yield signals above 0.4 K and $9.9 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$ (90% C.L.) for those that can yield signals above 15 K. For nuclearites that cannot penetrate the Earth (lighter than 0.1 g), these limits should be doubled.

In order to compare with other experiments which usually express the limits as a function of $\beta$, we have calculated the acceptance of the detector corresponding to energy cuts at 0.4 and 15 K, respectively (Fig. 2). It is seen from Fig. 2 that the corresponding "$\beta$ cutoffs," which we take as such a value that the acceptance of the detector is reduced to 85%, are at $10^{-3}$ and $2.5 \times 10^{-3}$, respectively {or these values times $[m/(1.5\ \mathrm{ng})]^{4/3}$ if $m > 1.5$ ng}. Figure 3 is the comparison of our result with some recent experiments[10,11] using scintillators.

The two scintillator experiments shown in Fig. 3 seem to be the only ones that have been explicitly analyzed for nuclearites by the original authors. Other experiments designed for magnetic monopole searches have yielded much lower flux limits for monopoles and may also be sensitive to nuclearites. De Rújula and Glashow[5,6] have analyzed the track-etch experiment with ancient mica[12] carried out by Price *et al.*, and have set a flux limit that is several orders of magnitude lower than those shown in Fig. 3. However, since the mica samples have been buried deep underground most of the time, this flux limit only applies to nuclearites heavier than $2.4 \times 10^{-10}$ g, while the sea-level experiments shown in Fig. 3 apply to nuclearites heavier than $1.5 \times 10^{-13}$ g. The mica samples may have spent a considerable amount of time near the Earth's surface and therefore may imply a significant flux limit for nuclearites much lighter than $2.4 \times 10^{-10}$, but such analysis has not been done. Several other experiments conducted at sea level or mountain altitude[13] to search for monopoles and other particles have also set flux limits comparable to or lower than those shown in Fig. 3, but they have not been explicitly analyzed for nuclearites. To show why one must be very careful when interpreting the results of monopole experiments for nuclearites, we consider an example. The monopole-search experiment[14] by Liss, Ahlen, and Tarlé using a thick slab of scintillator has probably set the best monopole flux limit among the sea-level scintillator searches, which is 1 order of magnitude lower than those shown in Fig. 3. However, a close look at its data show that about 820 events have saturated their amplifiers during the observation. Although these events can be rejected as monopoles, they cannot be ruled out as nuclearites, and therefore, the flux limit from this experiment is considerably

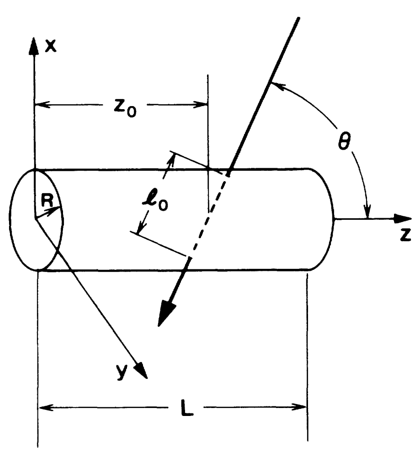


FIG. 1. Definitions of the geometrical parameters in Eq. (4).

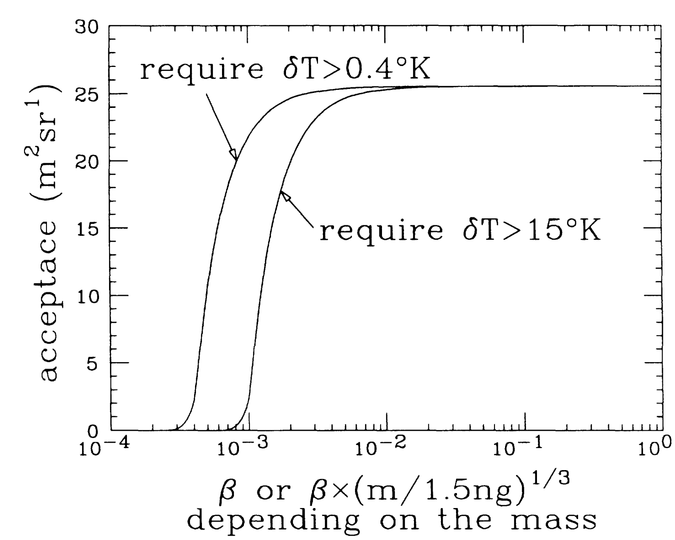


FIG. 2. The acceptance of the Stanford gravitational-wave detector to nuclearites with energy cuts at 0.4 and 15 K. The horizontal axis depends on the nuclearite's mass; for $m < 1.5$ ng, it is simply $\beta$, while for $m > 1.5$ ng, it represents the quantity $\beta[m/(1.5\ \mathrm{ng})]^{1/3}$.

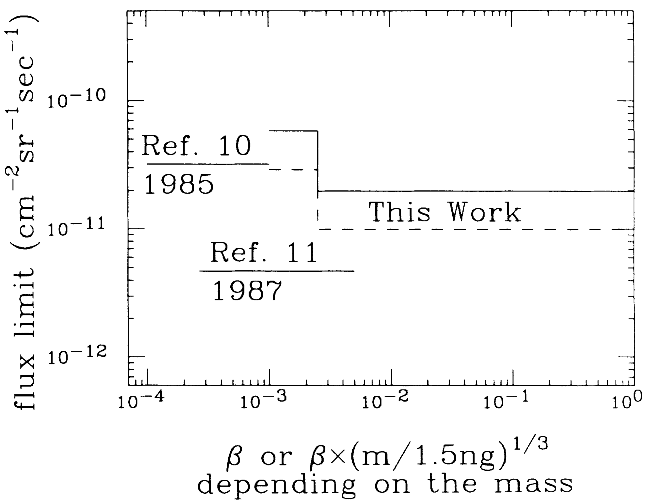


FIG. 3. The flux limit of nuclearites obtained from the data of a 252-h run of the Stanford gravitational-wave detector, compared with two recent scintillator experiments. The limit applies only to nuclearites heavier than $1.5\times10^{-13}$ g (e.g., those that can penetrate the atmosphere). For the gravitational-wave detector limit, the horizontal axis depends on the nuclearite's mass. For $m<1.5$ ng, the horizontal axis is $\beta$, while for $m>1.5$ ng, it represents the quantity $\beta[m/(1.5\ \text{ng})]^{1/3}$. The scintillator limits are identified by the reference and the year of publication. For them, the horizontal axis is always $\beta$. For nuclearites that can penetrate the Earth (heavier than 0.1 g) the limit is a factor of 2 lower, as shown by the dashed line.

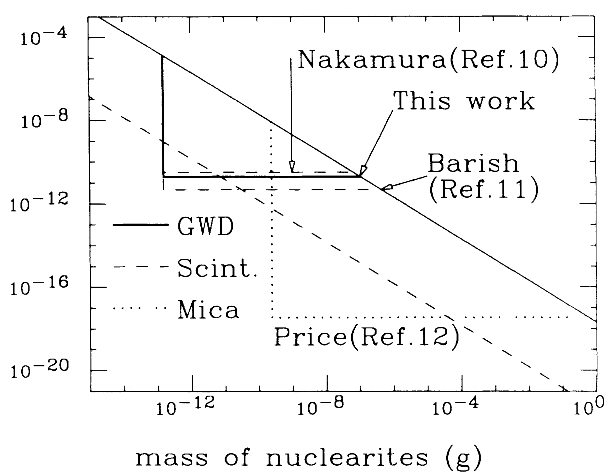


FIG. 4. The flux limits as a function of mass from experiments that have been explicitly analyzed for nuclearites, compared with the expected dark-matter flux. The solid diagonal line is the expected galactic-halo dark-matter flux and the dashed diagonal line is the dark-matter flux required to close the Universe. The limit from each experiment is identified by the first author and the reference number. Different textures are used to indicate the type of detectors.

worse than those shown in Fig. 3. Without knowing much of the technical details of other monopole search experiments, we do not attempt to interpret their results for nuclearites in this short Letter, but simply compile those that have been *explicitly* analyzed for nuclearites. Figure 4 is such a compilation of flux limits as a function of mass, compared with the expected dark-matter flux. Although the flux limit from gravitation-wave detectors is not the best one, it is already significant enough to rule out nuclearites in a certain mass range as a dark-matter candidate, for both the galactic halo dark matter and the dark matter required to close the Universe.

To conclude, present resonant-bar gravitational-wave detectors are effective nuclearite detectors. Even a short early run of the Stanford gravitational-wave detector already yields a flux limit that is significant enough to rule out nuclearites in a certain mass range as a dark-matter candidate. It is interesting to note that this seems to be the first flux limit for any particle that has been obtained by acoustic and mechanical detection techniques. Better data of gravitational-wave searches are becoming available now and they could be analyzed to search for nuclearites more sensitively. The actual signal shape and the coincidence between normal modes may be a powerful tool to reject background noise. We expect that the full analysis of existing data will improve the flux limit by several orders of magnitude compared with this work.

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