A search for evidence of nuclearites in astrophysical pulse experiments

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De Rújula and Glashow[1] have suggested that nuclearites, aggregates of up, down and strange quarks in roughly equal proportions, may form a component of the material reaching the Earth from the Galaxy. On traversing the atmosphere they will look something like meteors, but will travel faster. The masses of these aggregates may vary over a wide range and their velocities will be typically 250 km s^{-1}, corresponding to the Sun's galactic rotation. If all the dark matter in the Galaxy is assumed to be in the form of nuclearites, a limit can be set to the incoming flux. We report here upper limits derived from four experiments, originally carried out to detect cosmic γ rays, as well as some derived by other authors, which would be sensitive to pulses of light from nuclearites in the lower atmosphere. Our upper limits are compatible with the suggested maximum flux and competitive with a search for tracks etched in mica[2], which could also be caused by nuclearites.

De Rújula and Glashow show that the visual magnitude of an atmospheric nuclearite:

$$M = 10.8 - 1.67 \log_{10}(m/10^{-6}) + 5 \log_{10}(h/10\ \mathrm{km}) \qquad (1)$$

where m is the mass of the nuclearite in grams and h its distance from the detector. The nuclearite will radiate predominantly in the lower atmosphere, effectively below:

$$h_{\max} = 2.7\ \mathrm{km}\ \ln(m/1.2\times10^{-5}\ \mathrm{g}) \qquad (2)$$

In our experiments, m ranged from 10^{-3} to 10 g, and $h_{\max}$ was typically 20-30 km, except in one case where it was constrained by the arrangement of the optical system.

The first five experiments that we consider were carried out at the Whipple Observatory, Arizona. The first[3], in 1969-72, used the 10-m reflector to search for γ rays from the Crab Nebula or, for pulsars in the 10^{11}-eV region. A total of 112 h of observation were taken at various zenith angles. To trigger the system, ~50 photoelectrons were required in an integration time of 10^{-8} s. In a subsequent analysis[4], a search was made in the data for bursts of events lasting up to 0.1 s. This analysis is the basis of the present discussion; 12 events were required to constitute a burst. The transit time through the field at a typical detectable height was ~10^{-2} s. To produce 12 events from random fluctuations in 10^{-2} s, with a basic integration time of 10^{-8} s, requires about a 4.5σ upward deviation from the mean light of the nuclearite in these 10^{-8} s intervals. (The night-sky background contribution[5] was small, ~10% of that from the nuclearite). Fifty photoelectrons are needed, σ therefore is 11.1, and $\sigma^2 = 123$, the mean number of photoelectrons per 10^{-8} s interval. With a 15% photocathode efficiency at the photomultiplier, we obtain a photon number of 823 photons in 10^{-8} s average illumination over the 10^{-2} s transit time. The area of the reflector was effectively 60 m^2, leading to a flux of 1.37×10^{-3} photons cm^{-2} in 10^{-8} s, or 1.37×10^{5} photons cm^{-2} s^{-1}. Converting this to erg cm^{-2} s^{-1} to obtain the visual magnitude[6] and taking 0 mag = 8.5×10^{-6} erg cm^{-2} s^{-1}, we obtain a limiting magnitude of 3. Combining equations (1) and (2) the mass became 0.16 g, $h_{\max}$ was 25 km, and a typical distance h was 15 km.

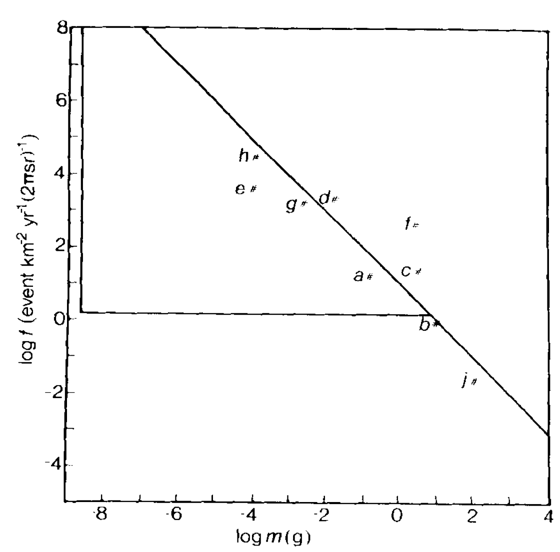

Fig. 1 Mass of the nuclearites plotted against incoming flux. The sources are detailed in Table 1.

Table 1 Cosmic flux limits for nuclearites of various masses

Ref.	Mirror diameter (m)	Mass (g)	Flux limit (events km^{-2} yr^{-1} $(2\pi\ \mathrm{sr})^{-1}$)	Point in Fig. 1
7	1.5 × 2	10	1.15	*b*
8	1.5 × 3	3	4.3	*c*
9	10 × 1	1.5×10^{-2}	1,700	*d*
10	10 × 1	10^{-4}	5,000	*e*
11	1.5 × 1	0.2	380	*f*
12	0.8 × 1	3×10^{-3}	1,710	*g*
13	1 × 1	10^{-4}	3.5×10^{4}	*h*
14	None, PM tubes only	250	0.013	j

The surface area of the conical frustum from 2.2 km (altitude of observatory) up to 25 km at a mean zenith angle of 25° and full field of view 1° was 16.6 km^2. Upward moving nuclearites occur for this mass, so the whole area is effective. The statistical upper limit, at the 99% level, from the burst analysis, was 477 events yr^{-1}. We therefore obtain an upper limit flux of 28.7 events km^{-2} yr^{-1} $(2\pi\ \mathrm{sr})^{-1}$, at a mass $m = 0.16$ g. This limit is plotted as *a* in Fig. 1, the diagonal line is the upper limit to the cosmic flux, derived by De Rújula and Glashow on the assumption that the entire dark matter of the Galaxy consists of nuclearites. The triangular area in Fig. 1 represents the limits derived in ref. 1 from an experiment by Price *et al.*[2] using the etching of tracks in buried mica samples, originally intended for the detection of monopoles. It will be seen that our limit falls below the maximal flux and is compatible with the mica experiment.

We are aware of eight other experiments which can be similarly analysed. Their main features are summarized in Table 1 and the resultant flux limits plotted in Fig. 1.

The results are generally comparable with those obtained in the mica experiment. Only that of Ogelman[14] can confidently be placed below both the maximal flux and the mica limit. Experiments designed specifically for nuclearite detection could, however, significantly reduce the limits by optical techniques.

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