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Nuclearite search with the TL stack detector

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Abstract. We present experimental results on the nuclearite search with the TL stack detector. The absence of penetrating tracks in the analysis of 6.6 m^2 of the TL stacks with an average exposure of 2.7 years yielded the 90 % C.L. nuclearite flux limit of 1.3×10^{-13} s^{-1}cm^{-2}sr^{-1}. Further results from the investigation of other 5.4 m^2 of the TL stacks with an average exposure of 4.4 years is also presented.

1 Introduction

Experiments searching for nuclearites have been performed (see for example Barish et al. (1987); Liu and Barish (1988); Ahlen et al. (1992); Astone et al. (1993); Ambrosio et al. (2000)) since Witten proposed (Witten, 1984) that quark matter consisting of aggregates of up, down and strange quarks in roughly equal proportions may exist and be stable and De Rújula and Glashow suggested several experimental techniques to detect them(De Rújula and Glashow, 1984; De Rújula, 1985).

In the search for slow and massive nuclearites, it is important to make different attempts because the responses of detectors have to be extrapolated from ordinary heavy-ion experiments or estimated from theoretical expectations. We have developed the TL stack detector and tried to detect nuclearites with it (Aglietta et al., 2001; Okei, 2001; Okei et al., 2001). In this paper, the recent analyzed result of the TL stack experiment is reported.

2 Experiment at LNGS

The procedure of the TL stack analysis is as follows: 1) we investigate the inner four X-ray films which are sandwiched between two TL sheets; 2) if we found coincident black marks (a track), then we investigate the other four X-ray films; 3) if the track found seemed to be a nuclearite event, we investigate position corresponding to the track on the TL sheets. The TL sheet analysis would provide information on the β-M relation of the nuclearite, if the number of background TL photons due to natural radio isotopes and cosmic rays is sufficiently small. Thus, 30 m^2 of TL stacks have been set at the LVD (Large Volume Detector) located in the underground laboratory of LNGS (Laboratori Nazionali del Gran Sasso), Italy.

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2.1 TL stack acceptance

At the underground site, the energy loss of nuclearites in rock must be taken into account in the calculation of the detector acceptance for different masses or velocities of nuclearites. (The average rock thickness cannot help us for this calculation since the acceptance for a thin rock thickness region cannot compensate the one for a thick region.) For example, to maintain $\beta \geq 10^{-3}$ after having traversed 4 km w.e. of rock, the initial β must be greater than 4×10^{-3} if the nuclearite mass $M = 5 \times 10^{13}$ GeVc^{-2}. Figure 1 shows the nuclearite velocity underground relative to the initial velocity as a function of the rock thickness traversed for $M = 10^{17}, 10^{16}, 10^{15}, 2 \times 10^{14}$ and 5×10^{13} GeVc^{-2}.

The cumulative TL stack acceptance relative to the maximum as a function of the rock thickness at the Gran Sasso underground laboratory is shown in figure 2. About 95% of the TL stack acceptance is covered by directions of rock thickness of less than 10 km water equivalent (w.e.).

Taking the nuclearite energy loss and the TL stack sensitivity (Aglietta et al., 2001; Okei, 2001; Okei et al., 2001) into account, we calculated the effective TL stack acceptance as shown in figure 3.

2.2 Background

Since usual relativistic particles cannot make their tracks in the TL stack detector unless they have charge of larger than 50 (Aglietta et al., 2001; Okei, 2001; Okei et al., 2001), they are of no concern to us as backgrounds in nuclearite search with the TL stack detectors even at sea level. High energy

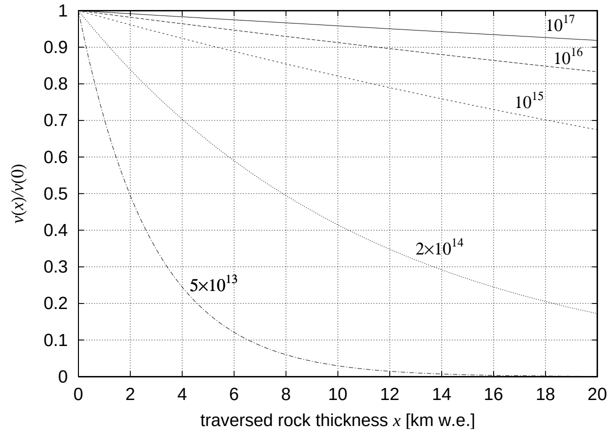

Fig. 1. The nuclearite velocity relative to the initial one as a function of material traversed for $M = 10^{17}, 10^{16}, 10^{15}, 2 \times 10^{14}$, and 5×10^{13} GeVc^{-2}.

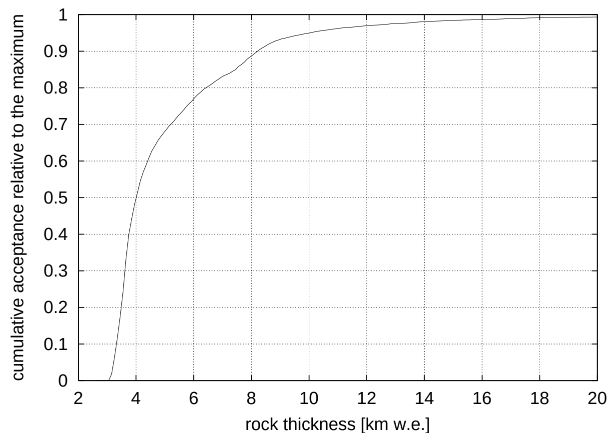

Fig. 2. The cumulative TL stack acceptance relative to the maximum as a function of rock thickness at the Gran Sasso underground laboratory.

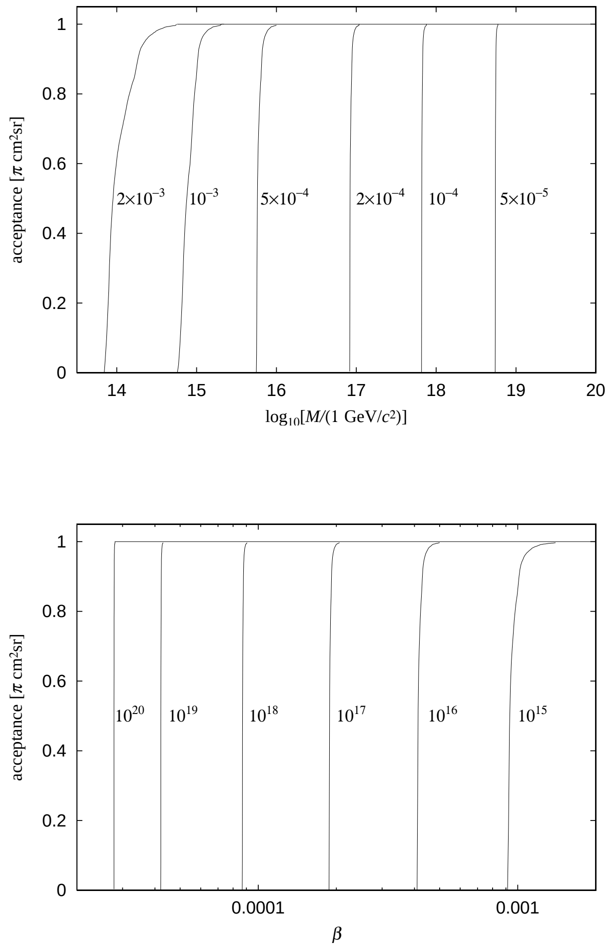

Fig. 3. The acceptance for nuclearites calculated for 1 cm^2 of the TL stack set at the LNGS underground laboratory as a function of M for several values of the initial β (top) and as a function of the initial β for $M = 10^{15}, 10^{16}, 10^{17}, 10^{18}, 10^{19}$ and 10^{20} GeVc^{-2} (bottom).

muon interactions, e^+e^- pair production, bremsstrahlung and photonuclear interactions, would not give a background either(Okei, 2001).

If dust containing natural radioisotopes such as radon is contained between a TL sheet and a X-ray film in a vacuum packed TL strack, radiations or fluorescence and phosphorescence from the TL sheet due to the radiations might make a visible black mark on the X-ray film. The probability that the accidental coincidence of such black marks (isotope events) mimic a nuclearite event depends on the site where the TL stacks are set. Here, we evaluate the chance probability simply for the experiment at the Gran Sasso underground laboratory.

The observed number of isotope events in one X-ray film is at most ∼20 including very small black marks undistinguishable from defects of the X-ray film. Vacuum packing provided us with the positional precision of few hundred microns. Thus, we calculated the chance probability by setting; the mean number of isotope events per X-ray film to be 100 and the positional precision to be 1 mm, in order to evaluate the upper bound.

Since the effective area of one X-ray film is 500 cm^2, the expected number $\mu_{\rm bin}$ of isotope events within a bin of area $S_{\rm bin}$ cm^2 is,

$$\begin{aligned}\mu_{\rm bin} &= 100 \times \frac{S_{\rm bin}}{500} \\ &= 0.2 S_{\rm bin} \qquad (1)\end{aligned}$$

and the probability $P_{\rm bin}(N)$ of observing N isotope events follows Poisson distribution

$$\begin{aligned}P_{\rm bin}(N) &= \frac{\mu_{\rm bin}^N}{N!}\exp(-\mu_{\rm bin}) \\ &= \frac{(0.2S_{\rm bin})^N}{N!}\exp(-0.2S_{\rm bin}). \qquad (2)\end{aligned}$$

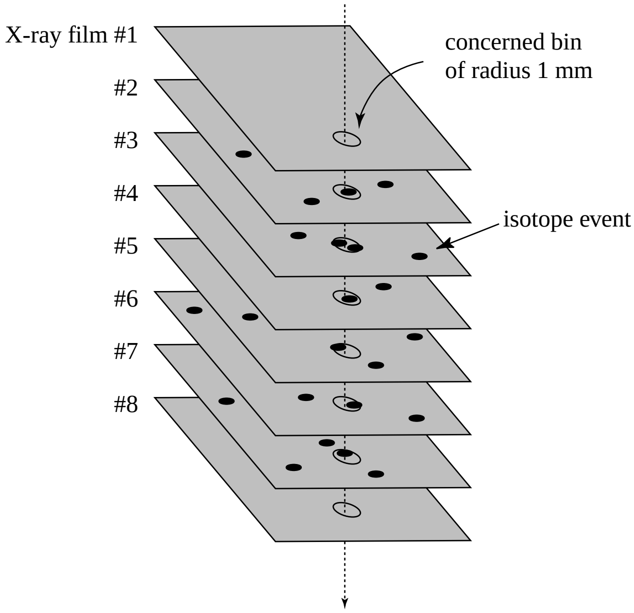

Fig. 4. A schematic diagram of a false nuclearite event.

Therefore, the probability of occurring a false nuclearite event within a circular bin of radius 1 mm ($S_{\rm bin} = 0.1^2\pi$ cm^2) is calculated as,

$$\begin{aligned} P_{\rm track} &= P_{\rm bin}(0)^2 \left(\sum_{N=1}^{\infty} P_{\rm bin}(N) \right)^6 \\ &= P_{\rm bin}(0)^2 (1 - P_{\rm bin}(0))^6 \\ &= \exp(-0.4 S_{\rm bin})(1 - \exp(-0.2 S_{\rm bin}))^6 \\ &= 0.9875 \times 6.038 \times 10^{-14} \\ &= 5.96 \times 10^{-14}. \end{aligned} \tag{3}$$

Here, a false nuclearite event is as follows; at least one isotope event exists in the bin on the all of inner 6 X-ray films and no black mark exists in the bin on the two outermost X-ray films (see figure 4).

Since $\mu_{\rm bin} \ll 1$ and $P_{\rm track} \ll 1$, the effective number of bins per one TL stack $NBIN_{\rm stack}$ can be written as,

$$NBIN_{\rm stack} = \frac{500}{S_{\rm bin}} = 15915.5, \tag{4}$$

and the probability $P_{\rm stack}$ of occurring at least one false nuclearite event in one TL stack is

$$\begin{aligned} P_{\rm stack} &= 1 - (1 - P_{\rm track})^{NBIN_{\rm stack}} \\ &= 9.49 \times 10^{-10}. \end{aligned} \tag{5}$$

Finally, if we analyze 1000 TL stacks, the probability $P_{\rm RI}$ of observing at least one mimic nuclearite event due to natural radioisotopes is,

$$\begin{aligned} P_{\rm RI} &= 1 - (1 - P_{\rm stack})^{1000} \\ &\sim 10^{-6}. \end{aligned} \tag{6}$$

This upper bound calculation shows that only one mimic event would be observed in 10^9 TL stacks, or the expected number of mimic events is 10^{-6} when we analyze 1000 TL stacks. Thus, we conclude that isotope events can not mimic nuclearite events.

3 Result

The absence of penetrating tracks in the analysis of 6.6 m^2 of the TL stacks with an average exposure of 2.7 years yielded the 90 % C.L. nuclearite flux limit of 1.3×10^{-13} s^{-1}cm^{-2}sr^{-1} (Okei, 2001; Okei et al., 2001). Recently, We investigated 5.4 m^2 of the TL stacks with an average exposure of 4.4 years. Since complete track was not found in the new analysis either, we set the combined 90 % C.L. upper limit for the downward flux of nuclearites as $F \leq 2.3$/(the acceptance $\times$ the exposure time) $\sim 5.6 \times 10^{-14}$ s^{-1}cm^{-2}sr^{-1} ($F \leq 2.8 \times 10^{-14}$ s^{-1}cm^{-2}sr^{-1} for the isotropic flux).

The limits for nuclearites of $\beta = 2 \times 10^{-3}$, 10^{-3} 5×10^{-4}, 2×10^{-4} and 10^{-4} at sea level are shown in figure 5. The diagonal line shows the maximum cosmic flux for each of β, which assumes that all dark matter consists for nuclearites (De Rújula and Glashow, 1984; De Rújula, 1985). Figure 6 shows the comparison of our limit for nuclearites of $\beta = 10^{-3}$ at sea level (the thick full curve) and some of the limits from several other experiments using various techniques: scintillators (Barish et al., 1987; Ahlen et al., 1992), gravitational-wave detectors (Liu and Barish, 1988; Astone et al., 1993) and CR-39 (Ambrosio et al., 2000).

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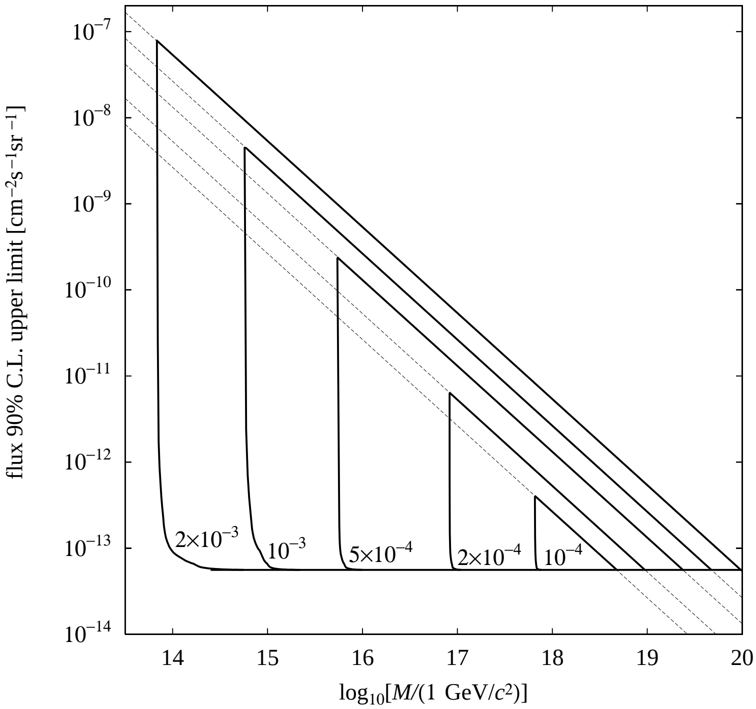

Fig. 5. The 90 % C.L. flux upper limits for nuclearites of $\beta = 2 \times 10^{-3}$, 10^{-3} 5×10^{-4}, 2×10^{-4} and 10^{-4} at sea level. The maximum cosmic flux for each of β is shown with the diagonal line.

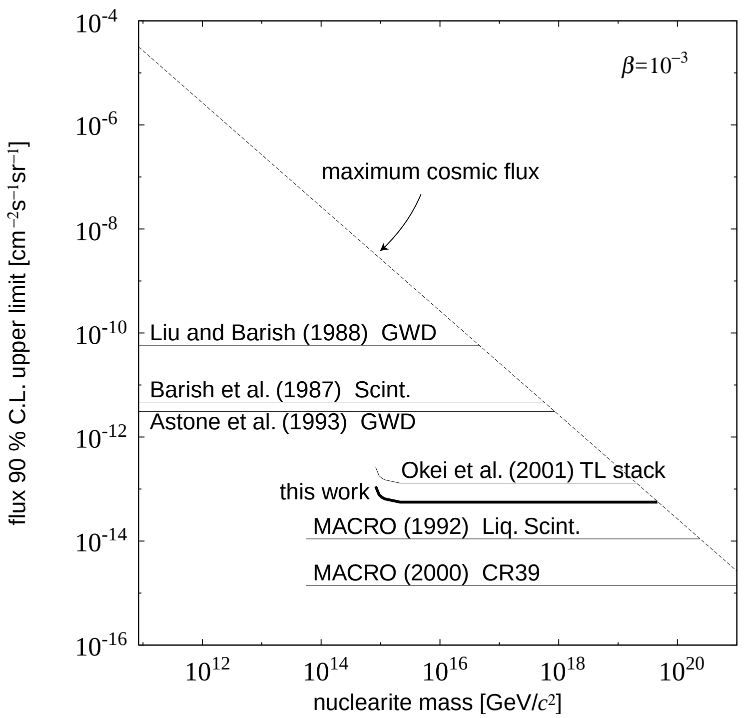

Fig. 6. The 90 % C.L. flux upper limits for nuclearites of $\beta = 10^{-3}$ at sea level. The thick full curve shows the limit from this work. The thin full curve labelled 'Okei et al. (2001)' is the limit reported in (Okei et al., 2001). The thin solid lines labelled 'MACRO (1992)' and 'MACRO (2000)' are the limits from (Ahlen et al., 1992) and (Ambrosio et al., 2000), respectively. The other three thin solid lines are the limits from (Barish et al., 1987; Liu and Barish, 1988; Astone et al., 1993) identified by the author and year of publication.