Proceedings of ICRC 2001: 1473 © Copernicus Gesellschaft 2001

ICRC 2001

The TL stack sensitivity to nuclearites

M. Aglietta[1], **C. Castagnoli**[1], **K. Iwata**[2], **Y. Kirihara**[3], **K. Kuga**[4], **M. Nakagawa**[4], **K. Okei**[3], **O. Saavedra**[1], **N. Takahashi**[5], **D. Ukai**[4], **T. Wada**[3], **I. Yamamoto**[4], **and Y. Yamashita**[3]

[1]Institute of Cosmo-Geophysics, CNR, Torino, University of Torino and INFN Torino, Italy
[2]Nara Medical University, Nara, Japan
[3]Department of Physics, Okayama University, Okayama 700-8530, Japan
[4]Okayama University of Science, Okayama, Japan
[5]Hirosaki University, Hirosaki, Japan

Abstract. It is shown that a thermoluminescent (TL) sheet stack detector, consisting of TL sheets and medical X-ray films, is an effective detector for slow and massive nuclearites. Nuclearite energy loss is not explicitly used for the estimation of the TL stack sensitivity to nuclearites, but implicitly by considering ways of energy depositions.

1 Introduction

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. This strange quark matter (also called 'strangelets') may have masses ranging from a few GeV to that of a neutron star. De Rújula and Glashow have termed such particles in cosmic rays colliding with Earth, 'nuclearites', and suggested several experimental techniques to detect them(De Rújula and Glashow, 1984; De Rújula, 1985).

Experiments searching for nuclearites have been performed using different techniques or the same technique but by different groups (see, for example Barish et al. (1987); Liu and Barish (1988); Ahlen et al. (1992); Astone et al. (1993); Ambrosio et al. (2000)). In the search for slow and massive nuclearites, say, velocities $\beta \lesssim 10^{-3}$ and masses $M \gtrsim 10^{10}$ GeVc^{-2}, the responses of detectors to nuclearites have to be extrapolated from ordinary heavy-ion experiments or estimated from theoretical expectations. Consequently, threshold values for the positive or negative detection of nuclearites depend on subjective choices of analysts: an overestimate of the response or a too conservative threshold may result in an exclusion of a weak signal or incorrect flux upper limits for nuclearites of undetectable mass or velocity, whereas an optimistic threshold with an underestimate of background events may result in a false positive detection. Thus, developments of different detection techniques and attempts to detect nuclearites with different techniques or by different groups are important.

Correspondence to: T. Wada
(wada@science.okayama-u.ac.jp)

We present here the development of a thermoluminescent (TL) sheet stack detector, i.e. a sandwich of TL sheets and medical X-ray films. The combination makes it more efficient and easier to track nuclearites than only TL sheet detectors (see section 3).

2 TL sheet sensitivity to slow ions

A TL sheet and its read-out system have been developed for studying hadronic and electromagnetic cascade showers (Imaeda et al., 1985; Okamoto et al., 1986; Yamamoto et al., 1987; Takahashi, 1988). The TL sheet is a mixture of $BaSO_4$:Eu doped and Teflon. The mixing ratio is 1 to 1 by weight.

Low velocity ions moving in matter lose their energy to the target electrons (called electronic stopping) and to the target nuclei (called nuclear stopping). In references Kuga et al. (1995) and Wada et al. (1995), the sensitivity of the TL sheet to a low velocity ion was estimated by assuming that it depends on how the incident ion loses its energy in $BaSO_4$ of the TL sheet,

$$N_{\rm TL} = a_{\rm e}\mathcal{E}\ell_{\rm e} + a_{\rm n}\mathcal{E}\ell_{\rm n} \tag{1}$$

where $N_{\rm TL}$ is the number of TL photons per ion, $\mathcal{E}\ell_{\rm e}$ and $\mathcal{E}\ell_{\rm n}$ are the total electronic and nuclear energy loss of the incident ion, respectively, and the constants $a_{\rm e}$ and $a_{\rm n}$ were determined from the experimental data for ^{40}Ar ions with energies 1, 2, 4, 8, 16 and 800 keV (β ranging from 2.3×10^{-4} to 6.6×10^{-3}). However, $\mathcal{E}\ell_{\rm n}$ is redistributed from recoil atoms to the target depending on the transferred energy T of each single collision and the displacement energy $E_{\rm d}$ of a lattice atom. That is, if $T > E_{\rm d}$, the recoil atom would leave its lattice position and it would lose energy to the target electrons and to the target nuclei, whereas if $T < E_{\rm d}$, it would release the energy as a phonon (Ziegler et al., 1985; Ziegler, 1996). Therefore, radiation effects from a same value of $\mathcal{E}\ell_{\rm n}$ due to a small number of hard collisions and due to a large number of soft collisions would be different. Hence, $\mathcal{E}\ell_{\mathrm{n}}$, or the specific energy loss, such as REL or LET, are not appropriate parameters for describing the TL sensitivity.

Accordingly, we have re-estimated the TL sensitivity by assuming that N_{TL} depends on how $BaSO_4$ of the TL sheet obtains energy (Okei, 2001; Okei et al., 2001). In order to do this, we used the 1998 version of the TRIM code (Ziegler et al., 1985; Ziegler, 1996) (TRIM98) which can follow every recoil until its energy drops below the lowest displacement energy of any target atom to obtain the energy loss to ionization I, vacancy production V and phonons P by both incident ions and recoil atoms. Figure 1 shows the fraction of energy deposited, I, V and P, from argon ions to $BaSO_4$. The default values of the displacement energy $E_{\mathrm{d}} = 20$ eV and the lattice binding energy $E_{\mathrm{b}} = 2$ eV were used in the TRIM98 simulation. Figure 1 also shows the fractions of energy loss $\mathcal{E}\ell_{\mathrm{e}}$ (full curve) and $\mathcal{E}\ell_{\mathrm{n}}$ (broken curve) for comparison.

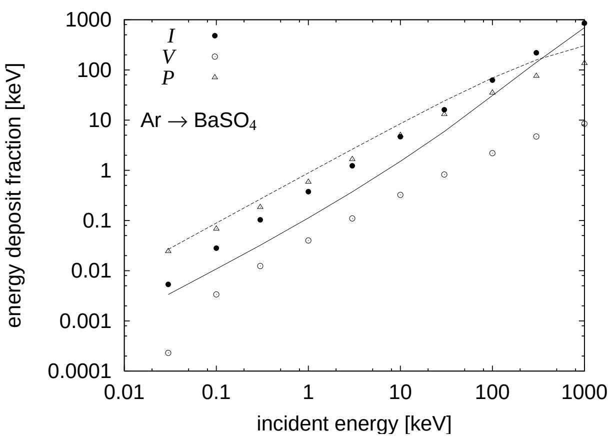

Fig. 1. The fractions of energy deposited, ionization I (full circle), vacancy production V (open circle) and phonons P (triangle) in $BaSO_4$ from argon ions. The energy loss fractions $\mathcal{E}\ell_{\mathrm{e}}$ (full curve) and $\mathcal{E}\ell_{\mathrm{n}}$ (broken curve) are also shown for comparison.

Since larger I corresponds to a larger number of ionized or excited electrons, which may be trapped and larger V corresponds to a larger number of vacancies, which may act as traps, we assume

$$N_{\mathrm{TL}} = a_I I + a_V V \tag{2}$$

where the constants a_I and a_V are determined experimentally as a_{e} and a_{n} of equation (1).

The determined values of a_I and a_V are 0.11 and 2.2 (I and V are in keV), respectively, and the calculated TL sensitivity is shown in figure 2 with the result of the argon ion experiment (full circle).

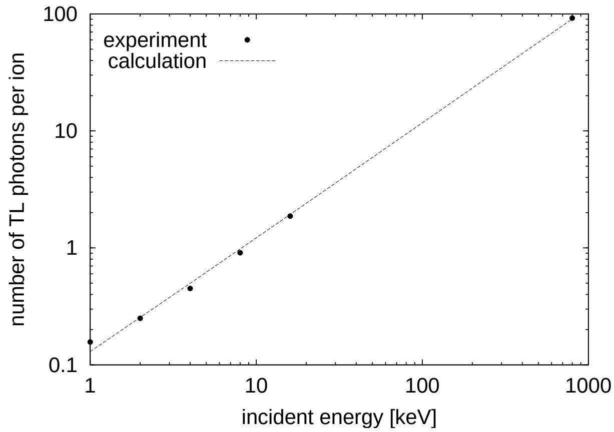

Fig. 2. The sensitivity of the TL sheet, N_{TL}, obtained from the low-velocity argon ion experiments. The broken line shows equation (2) calculated with $a_I = 0.11$ and $a_V = 2.2$.

3 TL stack sensitivity to nuclearites

The maximum cosmic flux of nuclearites is expected to be small (De Rújula and Glashow, 1984; De Rújula, 1985). Thus, large area of the TL sheets should be easily read when searching for nuclearites. To solve this problem, the TL stack detector consisting of the TL sheets and medical X-ray films (FUJI New RX) was designed as shown in figure 3. Though the X-ray films would not respond to nuclearites immediately, they do respond to fluorescence or phosphorescence (LTL, low-temperature luminescence) of the TL sheets. Therefore, we can search for evidence of nuclearites by scanning the X-ray films and searching for a track. The TL stacks are vacuum-packed doubly to make the X-ray films cling to the TL sheets. The two outermost X-ray films are covered with black papers in order to distinguish heavily ionizing particles from nuclearites. The total thickness of the TL stack is about 1 g cm^{-2}.

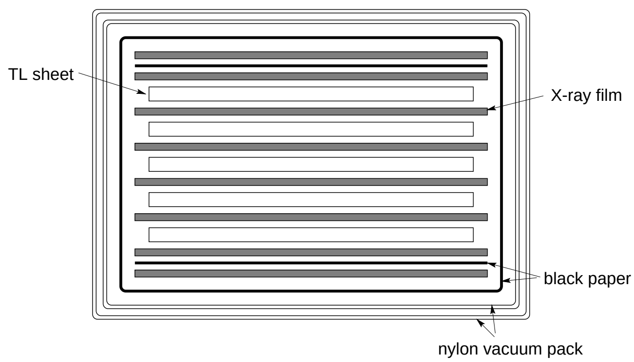

Fig. 3. A schematic diagram of the TL stack. The effective size of one TL stack is $20 \times 25\ \mathrm{cm}^2$.

Owing to the fact that LTL of the TL sheet is proportional to TL, the TL stack sensitivity to nuclearites can be evaluated in terms of the number of TL photons, N_{TL}, from the nuclearite penetration of the TL sheet. The evaluation is separated into two parts: how many photons are needed to make a black mark on the X-ray film, and how many photons would be emitted as a result of the nuclearite penetration ?

3.1 X-ray film sensitivity to TL photons

A TL sheet was irradiated by ^{90}Sr β-rays and an X-ray film was in contact with the TL sheet immediately after the irradiation for the purpose of determining the minimum number of LTL photons (i.e. the minimum number of corresponding TL photons) to produce a visible black mark on the X-ray film. It was found that 300 ^{90}Sr β-rays are sufficient to make a visible mark to the naked eye. Since the measured average number of TL photons per one ^{90}Sr beta-ray is about 3000, the expected number of TL photons due to 300 ^{90}Sr β-rays is 9×10^5 and we take $N_{\rm TL} = 10^6$ as the threshold value. (Note that only phosphorescence photons could contribute in the ^{90}Sr source experiment because the X-ray film was contacted to the TL sheet 'after' the irradiation.) If we try to detect nuclearites with the TL sheets only (without the X-ray films), more than 10^7 TL photons would be needed since the photon counting efficiency of the two dimensional TL readout system is 1.5×10^{-6}. Therefore, the X-ray films not only ease the scanning process, but also improve the detection efficiency by more than one order of magnitude.

In addition to the ^{90}Sr source experiment, the TL stack was exposed to heavy-ion beams at HIMAC of NIRS (National Institute of Radiological Sciences, Japan). Though only the preliminary result of this experiment is available, it was found that the charge of the penetrating ion must be larger than ∼50 to make a track in the TL stack. Thus, even iron ions cannot give a background in a nuclearite search with the TL stack.

As an example of visible black marks, figure 4 shows an X-ray film image of the TL stack exposed to $^{132}_{54}$Xe ions of 160 A MeV which yield about 3×10^6 TL photons per ion.

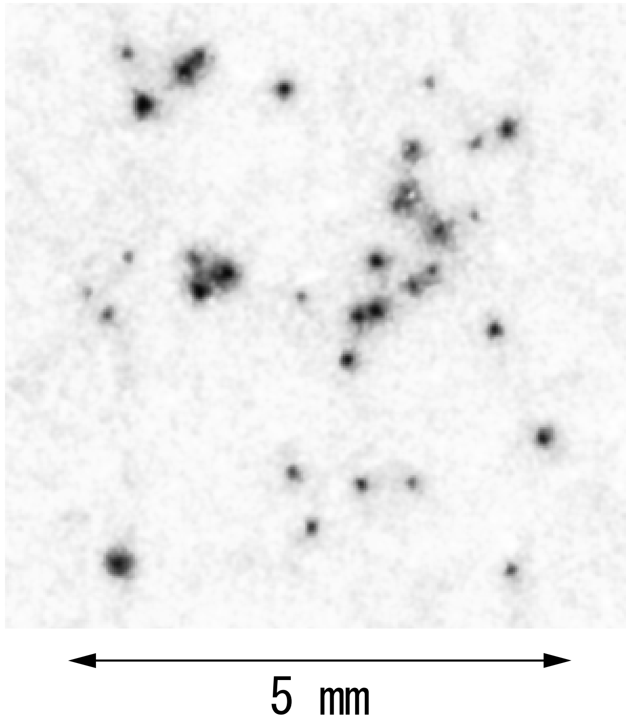

Fig. 4. An X-ray film image of the TL stack exposed to Xe ions of 160 A MeV.

3.2 TL sheet sensitivity to nuclearites

We assume that the main energy loss mechanism for a massive nuclearite passing through matter is by hard-sphere collisions with atoms, and the rate of energy loss is

$$\frac{{\rm d}E}{{\rm d}x} = -A\rho v^2 \tag{3}$$

where A is the effective cross sectional area of the nuclearite, v is its velocity, and ρ is the density of the medium (De Rújula and Glashow, 1984; De Rújula, 1985). If the size of a nuclearite is larger than an atom ($R_{\rm N} \gtrsim 1$ Å), the nuclearite would be like a neutron star and its cross sectional area would be simply $\pi R_{\rm N}^2$, whereas the size of a smaller nuclearite is governed by its electronic atmosphere which is never smaller than ~ 1 Å(De Rújula and Glashow, 1984; De Rújula, 1985). Thus, we take

$$A = \begin{cases} \pi \left(\dfrac{3M}{4\pi\rho_N}\right)^{\frac{2}{3}} & M \geq 1.5 \quad {\rm ng} \\ \pi \times 10^{-16}\ {\rm cm}^2 & M < 1.5 \quad {\rm ng} \end{cases} \tag{4}$$

where $\rho_{\rm N} = 3.6 \times 10^{14}$ g cm^{-3} is the density of strange quark matter (De Rújula and Glashow, 1984; De Rújula, 1985).

To estimate $N_{\rm TL}$ due to nuclearites with equation (2), that is, to calculate I and V due to nuclearites in $BaSO_4$, those of recoil atoms, barium, sulfur and oxygen, were calculated with TRIM98 (Okei, 2001; Okei et al., 2001). The total number of collisions N is

$$N = \rho_{\rm atom} A d \tag{5}$$

where $\rho_{\rm atom} = 6.9 \times 10^{22}$ cm^{-3} and $d = 0.013$ cm are the atomic number density and effective thickness of $BaSO_4$, respectively. We assume the number of collisions for each of the target atom to be proportional to the stoichiometric abundance, $N_{\rm Ba} : N_{\rm S} : N_{\rm O} = 1 : 1 : 4$. From these values and figure 5 of Okei et al. (2001), I and V due to nuclearites can be easily calculated because the recoil energy distributions are flat for the hard-sphere collisions. Figure 5 shows the estimated number of TL photons $N_{\rm TL}$ for a nuclearite of $M = 10^{21}$ GeVc^{-2} as a function of β. The thick and thin full curves show $N_{\rm TL}$ estimated for the case $E_{\rm d} = 20$ and 10 eV, respectively ($E_{\rm b} = 2$ eV for both cases). The old estimate of $N_{\rm TL}$ obtained as an explicit function of $\mathcal{E}\ell_{\rm n}$ with equation (1) is also shown by the broken curve for comparison.

The new estimates (the full curves) begin to deviate from the old estimate at $\beta \sim 4 \times 10^{-5}$. Consequently, the new estimates indicate that nuclearites of $\beta = 10^{-5}$ and $M = 10^{21}$ GeVc^{-2} are undetectable, whereas the old estimate indicates that they are detectable. The deviation is caused by the fact

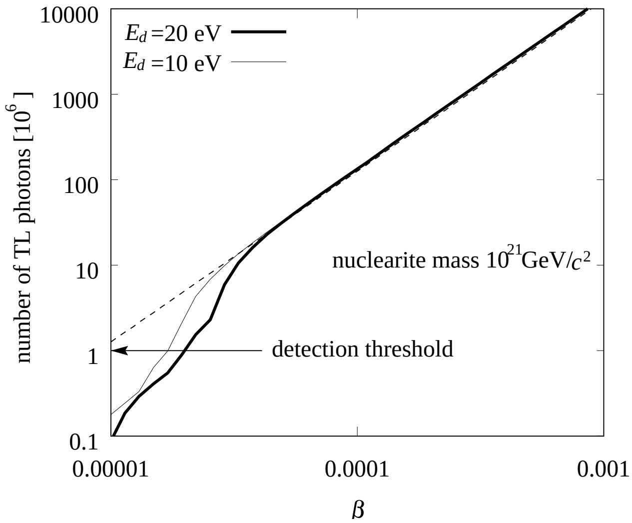

Fig. 5. The estimated number of TL photons N_{TL} for the nuclearite of $M = 10^{21}$ GeVc^{-2} as a function of β. The thick and thin full curves show N_{TL} estimated for the case $E_{\mathrm{d}} = 20$ eV and 10 eV, respectively ($E_{\mathrm{b}} = 2$ eV for both cases).

that as the velocity of the nuclearites decreases, the fraction of $\mathcal{E}\ell_{\mathrm{n}}$ deposited in $BaSO_4$ as P, which would not contribute to TL emission, increases. For example, the lightest atom, oxygen, cannot obtain enough energy to leave its lattice site from nuclearites of $\beta \lesssim 2.6 \times 10^{-5}$ if $E_{\mathrm{d}} = 20$ eV. (The possibility that target atoms could be displaced by huge nuclearites are ignored here to calculate lower bounds.)

Now it is clear why we should have re-estimated N_{TL} due to nuclearites. Although figure 5 also indicates that the choice of E_{d} is important at $\beta \lesssim 3 \times 10^{-5}$, we take $E_{\mathrm{d}} = 20$ eV as a modest value. The β–M region of nuclearites detectable with the TL stack is shown in figure 6.

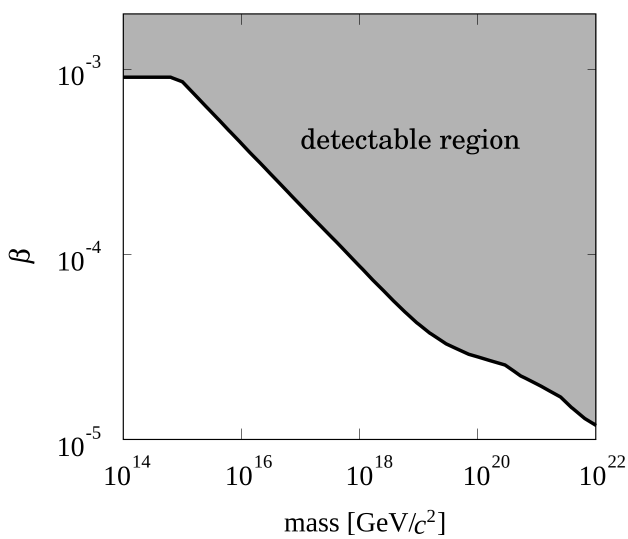

Fig. 6. The β–M region of nuclearites detectable with the TL stack for $E_{\mathrm{d}} = 20$ eV.

4 Summary

We have developed the TL stack detector. The TL stack sensitivity to nuclearites is estimated by the new model which is not an explicit function of nuclearite energy loss. The new model would be robuster when we estimete the sensitivity to slower nuclearites.

Acknowledgements. We wish to thank the LVD collaboration for permission to put the TL stacks in the LVD apparatus. We are grateful to Mr Alberto Romero, Mr Roberto Bertoni and their colleagues for their various help. We thank the staff of NIRS for the heavy-ion experiments at HIMAC. We also thank Mr Noriaki Sakurai and Mr Yutaka Aoki for helping the X-ray film analysis.

References

Ahlen, S. et al. 1992 *Phys. Rev. Lett.* **69** 1860
Ambrosio, M. et al. 2000 *Eur. Phys. J.* C **13** 453; Ambrosio, M. et al. 1999
Astone P et al. 1993 *Phys. Rev.* D **47** 4770
Barish, B., Liu G and Lane C 1987 *Phys. Rev.* D **36** 2641
De Rújula, A. and Glashow, S.L. 1984 *Nature* **312** 734
De Rújula, A. 1985 *Nucl. Phys.* A **434** 605c
Imaeda, K. et al. 1985 *Nucl. Inst. Meth.* A **241** 567
Kuga, K. et al. 1995 *Proc. 24th Int. Cosmic Ray Conf.* **1** 1015 (Note: Some graphs in Kuga et al. have errors.)
Liu, G. and Barish, B. 1988 *Phys. Rev. Lett.* **61** 271
Okamoto, Y. et al. 1986 *Nucl. Inst. Meth.* A **243** 219
Okei, K. 2001 *PhD Thesis* (in Japanese)
Okei, K. et al. 2001 *J. Phys.* G **27** 855
Takahashi, N. 1988 *Nucl. Inst. Meth.* A **270** 347
Wada, T. et al. 1995 *Reports of the Research Laboratory for Surface Science, Faculty of Science, Okayama Univ.* **7** 191–198

Witten, E. 1984 *Phys. Rev.* D **30** 272
Yamamoto, I. et al. 1987 *Nucl. Inst. Meth.* A **256** 567
Ziegler J F, Biersack J P and Littmark U 1985 *The Stopping and Range of Ions in Solids* Pergamon Press
Ziegler J F 1996 *The Stopping and Range of Ions in Matter Instruction Manual* IBM-Research, 28-0 Yorktown, NY, 10598, USA See `http://www.research.ibm.com/ionbeams/` for the latest version.