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PHYSICAL METHODS AND INSTRUMENTATION

CORRELATION BETWEEN IONIZATION AND DISPLACEMENT DAMAGE IN SILICON DETECTORS FOR ENERGIES OF INTEREST IN ASTROPARTICLE AND PARTICLE PHYSICS APPLICATIONS*

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Abstract. The use of semiconductors as detectors for particle and astroparticle physics imposes the understanding of the processes produced in material, their effects on the electronic properties, in their microscopic structure and at the device level. Calculations of LET and NIEL for different ions including hypothetical exotic particles put into evidence the peculiarities of these interactions.

Key words: ionization, displacement damage, silicon, ions, hypothetical particles.

PACS: 61.80.Az Theory and models of radiation effects
61.82.Fk Semiconductors
14.80.-j Other particles (including hypothetical)

1. ENERGY LOSS PROCESSES IN THE INTERACTION OF RADIATION WITH SEMICONDUCTORS

The processes of interaction of a radiation field with the semiconductor can be seen as aspects of a sequence. The projectile, which is the particle that produces interactions in the material, has both energy and momentum which could be transferred to the target.

In these processes, electrons could be removed from their normal orbits, and the atoms of the host material or the impurities pre-existent in the lattice could be knocked out of their normal sites. So, the energy transferred to the target is imparted between the two types of interactions: excitations or ionizations and lattice degradation. Thus, the energy transferred is the sum of the recoil energies, possible internal excitation energies, ionization and production of phonons. The

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primary knock-on nucleus (recoil), could produce the displacement of a new nucleus, if its energy is large enough, and the process continues as long as the energy of the colliding nucleus is higher than the threshold for atomic displacements. This phenomenon can be regarded as a cascade process. Below the threshold energy, the kinetic energy is transferred only to phonons.

The effects of ionization on defect formation in semiconductors are not too well understood and remain an open problem; see for example the work of Ascheron *et al.* [1].

Also, ionisation effects have been extensively studied in relation to detection aspects and their biological effects. But the correlated investigations of all aspects as simultaneous and competitive processes become significant in the conditions of the new generation of physics experiments in space or new space initiative.

2. EXPECTED BEHAVIOUR OF INCIDENT HEAVY IONS IN SILICON

Particle astrophysics and cosmology provide several opportunities for discoveries in fundamental physics that are complementary to those from accelerator experiments. In the present paper, we concentrate especially on the aspects related to heavy ions and we suggest the peculiarities of the behaviour of the hypothetical strange quark matter (SQM). The numerical simulations were performed using the SRIM code version 2006.02 [2].

Strange quark matter is another state of matter [3]. As is known, quarks and gluons carry colour charges. The confinement character of the strong force prohibits the isolated existence of single quarks, but they can cluster in pairs or small groups, as mesons $(q\overline{q})$, baryons (qqq) or antibaryons $(\overline{qqq})$ which have a net zero charge colour. There is no basic physical principle known which excludes the existence of larger baryons. Strange quark matter (so-called because of the admixture of strange quarks with the up and down quarks) is named in different forms in the literature: quarks nuggets, nuclearites, strangelets, corresponding to different range of masses and origin [4].

SQM should have relatively small positive integer charge and the neutrality is realized by the existence of electrons, analogous to the case of atoms.

The unusual properties: stability, the large mass range, low charge to mass ratio, low energy, is considered characteristic for SQM. In particular, the low ratio Z/A has been recognized as a crucial signature for experimental identification of strangelets. If for ordinary nuclei the Z/A ratio is usually between 0.33÷0.67, in colour flavour locked SQM (structures where quarks with different colour and quantum numbers form Cooper pairs) the Z/A ratio is $\approx 0.3 \times A^{-1/3}$ and thus in ordinary strangelets it is approximately constant for small *A*, $A^{-2/3}$ for large *A*, reaching $A^{-1/3}$ only asymptotically [5, 6].

The strangelets are expected to have approximately twice the density of normal nuclei and thus have a radius given by

$$R = 0.95 \times A^{1/3} \text{ fm}.$$

Two interesting events (hypothetical candidates for colour flavour locked SQM) were found in the analysis of AMS-01 data. One was measured as ^{16}He, with $Z = 2$ and *A* about 16, and the second is possibly ^{54}O with $Z = 8$ and $A = 54 + 8\ (-6)$ [7].

In Fig. 1, the preliminary results obtained for the ratio between the energy lost by ionization and the energy lost in atomic collisions, for the ions of He, O, Fe, U and for the two hypothetical candidates for SQM, previously mentioned, are presented for the energy range between 50 keV and 50 MeV.

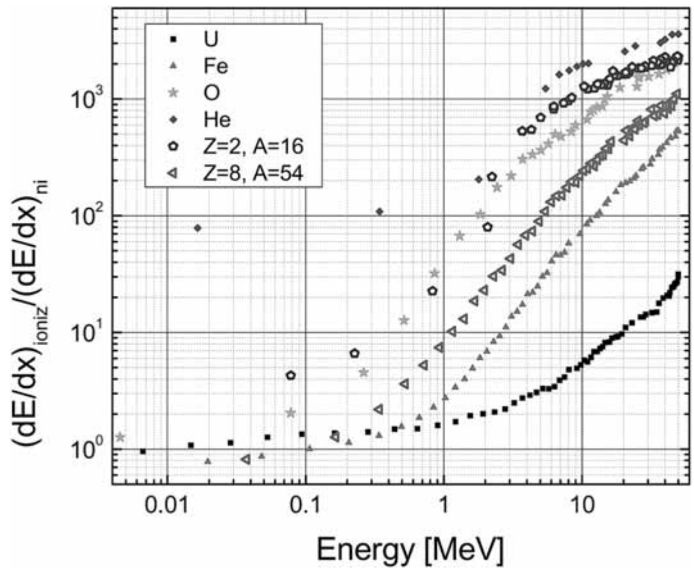

Fig. 1 – Ratio between ionizing and non-ionizing energy loss for ions of He, O, Fe, U, and for two hypothetical candidates for SQM.

In Figs. 2 a), b), c), d) and e), the spatial development of collision cascades calculated with SRIM for Si irradiated with the same ions of 25 keV, 150 keV and 1 MeV is represented. Only 10 ions were simulated in each case – the results are not statistically significant, but permit to visualize the distribution of recoils.

These preliminary results suggest an enhancement of defect formation due to atomic collisions in respect to ionization, for decreasing incident ion energy, for all ions. This phenomenon is more important for heavier ions. Below 200 keV, the

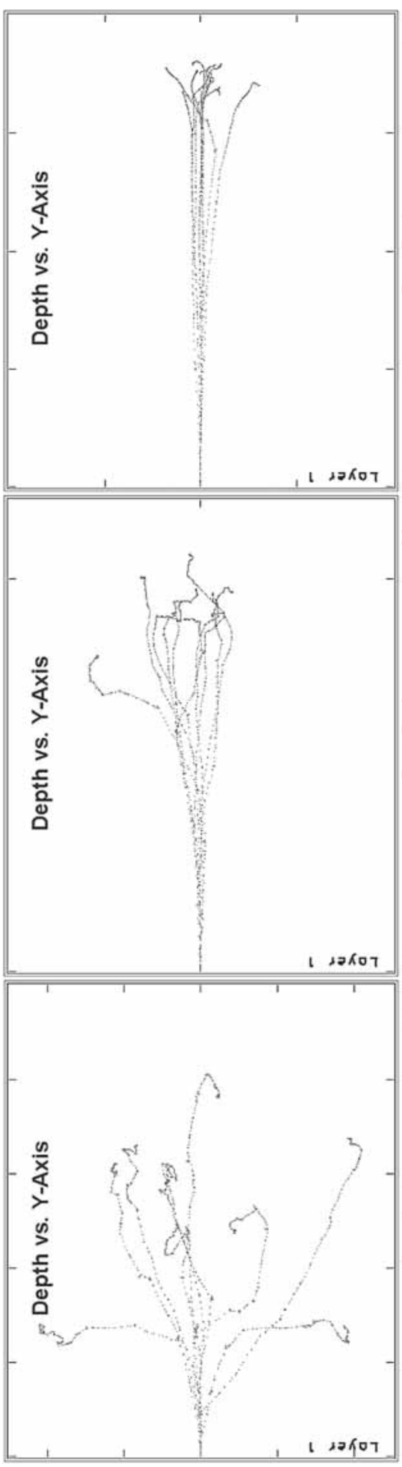

Fig. 2 a) – Collision cascades calculated with SRIM for Si irradiated with He ions of (from left to right) 25 keV, 150 keV and 1 MeV kinetic energy.

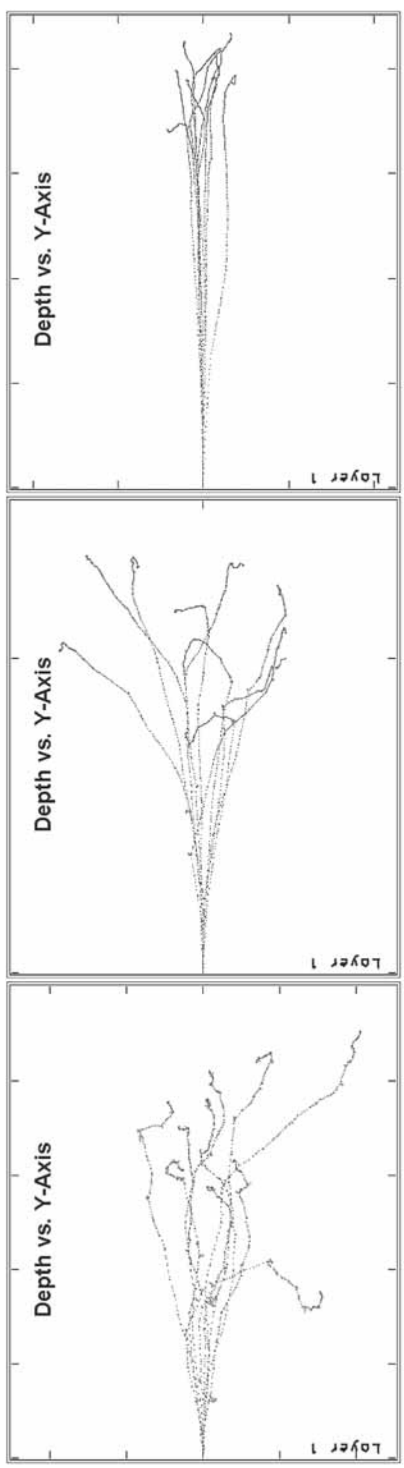

Fig. 2 b) – Collision cascades calculated with SRIM for Si irradiated with exotic SQM candidate He (Z = 2, A = 8) (from left to right) 25 keV, 150 keV and 1 MeV kinetic energy.

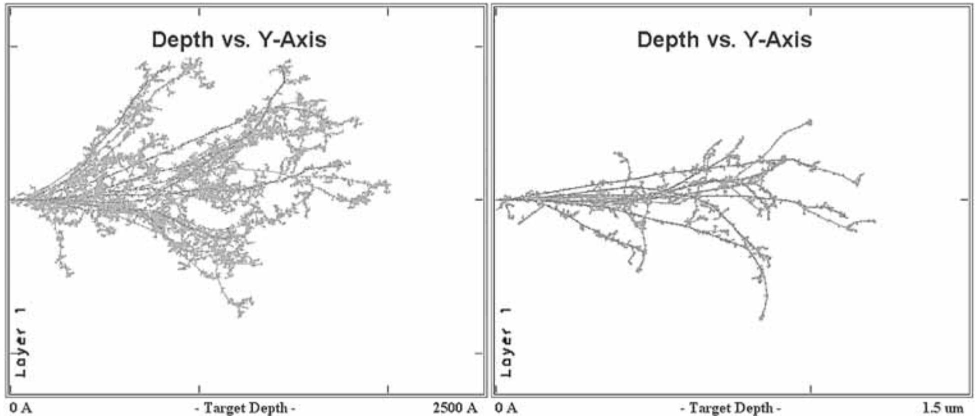

Fig. 2 c) – Collision cascades calculated with SRIM in Si irradiated with Fe ions with (from left to right) 25 keV, 150 keV and 1 MeV kinetic energy.

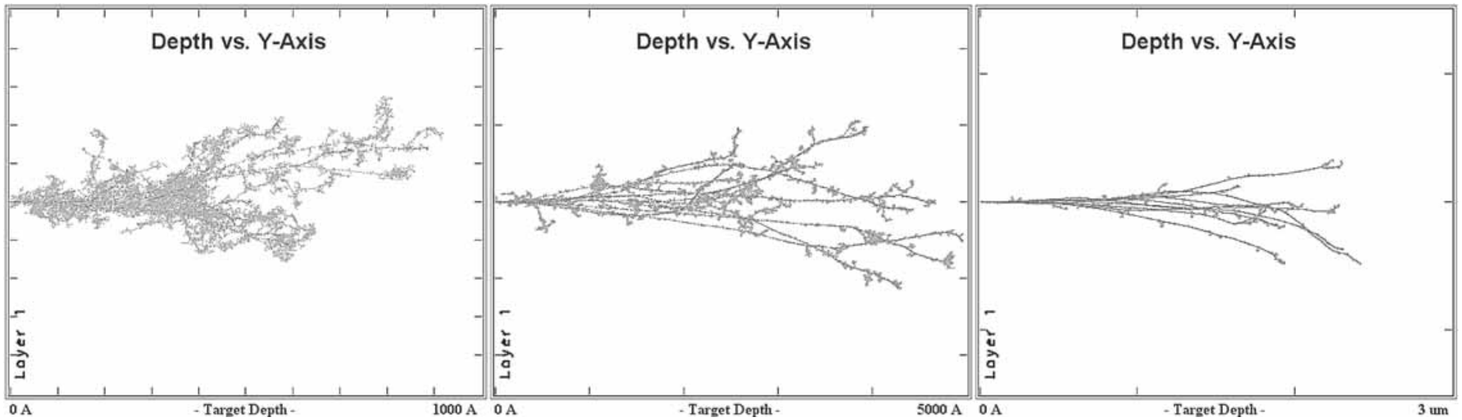

Fig. 2 d) – Collision cascades calculated with SRIM in Si irradiated with the exotic SQM candidate O ($Z = 8$, $A = 54 + 8 - 6$) of (from left to right) 25 keV, 150 keV and 1 MeV kinetic energy.

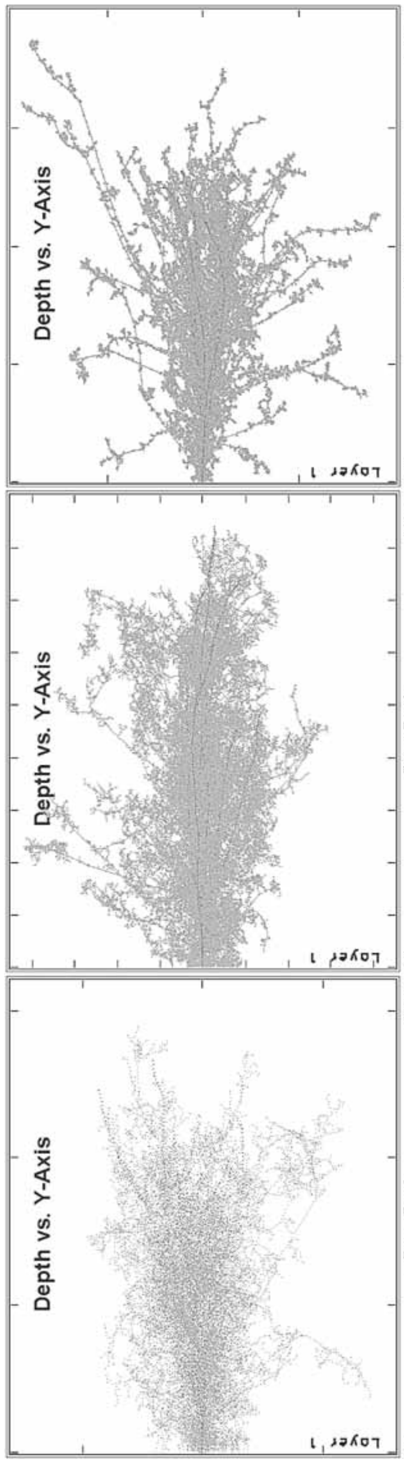

Fig. 2 e) – Collision cascades calculated with SRIM in Si irradiated with U ions of kinetic energy (from left to right) 25 keV, 150 keV and 1 MeV.

contribution of atomic collisions becomes comparable or higher than ionization. For the same charge number, the effect of atomic collisions is enhanced in respect to ionization. For the same atomic number of incident ions, the enhancement of non-ionizing energy loss is more pronounced for higher charge number and with the increase of the energy. For the "exotic" incident particles considered here, the bulk structural degradation is more important than for the corresponding normal ions.

The mechanisms of enhancement of bulk defect formation by ionisation could be understood as a consequence of the change in the binding energy of the nuclei in the lattice structure. Recoils, manifested as vacancies and interstitials in the silicon lattice change the hybridisation of the local bonding around coordination defects and thus possible energy levels in band gap are introduced [8].

If the present predicted results are confirmed by experimental data, these studies could open new possibilities in the understanding of phenomena at the frontier between nuclear and atomic physics.

3. SUMMARY

For low energies, the contribution of atomic collisions is comparable with or higher than ionization and this behaviour is a function of the charge and atomic numbers. For "exotic" incident particles, the bulk structural degradation is more important than for the corresponding normal ions.

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