Romanian Reports in Physics, Vol. 61, No. 2, P. 215–221, 2009

FROM NUCLEAR MATTER TO STRANGE QUARK MATTER – SOME CHARACTERISTICS OF THE INTERACTIONS IN ORDINARY MATTER*

I. LAZANU[1], M. CHERA[1], R. IORDĂNESCU[1], C. NIȚĂ[1], S. LAZANU[2]

[1]*University of Bucharest, Faculty of Physics, Department of Atomic and Nuclear Physics POBox MG-11, Bucharest-Măgurele, Romania*

[2]*National Institute of Materials Physics, POBox MG-7, Bucharest-Măgurele, Romania*

(Received July 2, 2008)

Abstract. The existence of Strange Quark Matter as a new stable or metastable form of existence of matter has been postulated by various authors quite a few years ago. Because until now a theory to predict the existence and the properties of these strangelets does not exist, it is absolutely necessary to investigate the peculiarities of their interactions with matter versus ordinary nuclear matter interactions.

In the present contribution, some peculiarities of the ionization and nuclear energy loss of strangelets with matter are investigated in comparison with ordinary ions, as a useful tool for their search. The rescattering mechanism could produce sub-threshold reactions and thus it is suggested as a possibility to discriminate between ordinary isotopes and very heavy (candidates for) strangelets with the same charge number.

Key words: strange quark matter, electron and nuclear energies losses.

1. INTRODUCTION – PRESENT STAGE AND DIRECTIONS IN THE SEARCH OF NEW FORMS OF NUCLEAR MATTER

The problem of the forms of existence of nuclear matter (as ordinary nuclear matter in the form of superheavy nuclei, hadronic matter, strange quark matter or atoms/nuclei made from charged black hole matter for example) represents an open field of investigation. In about 40 years between the pioneering papers of A. R. Bodmer [1] and E. Witten [2], and the present time, the existence of Strange Quark Matter was not yet firmly confirmed and a theory does not exist. Its hypothetical existence must be accepted in spirit of democracy of the laws of physics.

---

* Paper presented at the Annual Scientific Conference, June 6, 2008, Faculty of Physics, Bucharest University, Romania.

Starting from the classical Bethe-Weizsäcker mass formulae, Swiatecki [3] suggests the extrapolation of this equation and finds hypothetical islands of stability in respect to fission for superheavy nuclei, with exceptional values for Z and A. In fact, a bubble of nuclear matter with positive charge is neutralized by electrons. The electrons have an essential contribution to stability considerations. In fact, vacuum polarization caused by virtual pairs and spontaneous formation of real electron-positron pairs in supercritical electric field of superheavy nuclei limits the maximum value of Z [4], but in fact this is yet an open problem. Strange nuclear matter is a nonexotic form of matter where one or more nucleons are replaced by strange baryons, introducing a new degree of freedom in the field of fundamental interactions. The extrapolation of the drop model in the strange sector was investigated some years ago, see for example the paper of Dover and Gal [5].

Strange quark matter, called strangelets in this paper, is an admixture of a large number of delocalized up, down and strange quarks. The (weak) decay of an s-quark from SQM into a d-quark would be suppressed or forbidden if the lowest single particle states are occupied. If the strange quark mass is lower than the Fermi energy of the u or d quark in such a quark droplet, the opening of a new flavour degree of freedom tends to lower the Fermi energy and hence also the mass of the strangelet.

Small stable strangelets have approximately equal numbers of u, d and s quarks. A slight deficiency of s quarks gives the strangelet a net positive charge of approximately $Z = 0.3 \times A^{2/3}$ for the colour-flavour locked model [2] or $Z = 0.1 \times A$, turning over to $Z \cong 8 \times A^{1/3}$ for large A, for the MIT bag model [6]. Recently, Benjamin Monreal [7], using these models for strangelets, built a periodical table of strangelets. For stranglets, unusual properties are predicted: large mass range, higher density than normal nuclei, and low charge to mass ratio.

Until now several searches using different existing experimental possibilities and techniques identified some singular events, hypothetical candidates for strangelets. In experiments devoted to the study of primary CR nuclei, anomalous events with values of charge Z =14 and mass numbers A = 350 and A = 450 respectively, with Z = 46 and A > 1000 and with Z = 20 and A = 460 have been observed, and have been reported [8]. A short-lived strangelet candidate with mass 7.4 GeV and charge $Z = -1$ was separated by the NA52 experiment [9]. Two events were put in evidence in the preliminary space experiment AMS-01 data: ^{16}He: Z = 2, A~16 and ^{54}O: Z = 8, A = 54+8(−6) [10]. Within more than four million He events collected by AMS-01, and one event having the ratio $Z/A = 0.114 \pm 0.01$, and a kinetic energy of 2.1 GeV, the flux of $5\times10^{-5}\ \left(\text{m}^2\times\text{sr}\times\text{s.}\right)^{-1}$ associated to this state was found. It must be mentioned that, in the frame of the model developed by Zhang and Su [11], the most probable characteristics of this event are: it has an internal quark composition (16u+3d+23s), corresponding to a mass of about A=17.5 amu, a radius of 1.992 fm and a life time of the order $\tau = 2.25 \times 10^{-8}$ s, suggesting that it is metastable and consequently able to be detected.

Apparently, the strangelets do not differ from ultra heavy isotopes of ordinary elements or strange nuclei. At rest, a strangelet of charge Z behaves like a heavy isotope of atomic number Z; it has the same number of electrons, etc. The differences could be caused by the possible effects associated with the degree of freedom of strangeness and the higher nuclear density.

In this paper, after the discussion on the present stage of the subject, we investigated some aspects of the interactions of SQM with ordinary matter that are not usually considered in its search. In some simplified hypotheses, the energy loss in electron interactions – a directly measurable quantity, is estimated simultaneously with the energy loss in nuclear interactions – a not directly measurable quantity; but which produces effects in the detector structure. In the case considered, of a material with a crystalline structure (silicon), at low energy, the nuclear interactions induced by a strangelet could produce a fluctuation in the leakage current of the detector which could be irreversible.

The possibility of discrimination between an isotope and a strangelet / heavy isotope, using the production of sub-threshold nuclear reactions in a "ping-pong" mechanism, is also discussed.

2. MODEL CALCULATIONS

2.1. ENERGIES LOSSES IN MATTER

One incident projectile (ion or strangelet) interacts with the electrons and with the nuclei of matter and it loses its energy in several processes, which depend on the nature of the particle and on its energy.

The problem of the charge state of ions penetrating in matter is one of the most relevant questions for studies on ion penetrating in solid targets, because the equilibrium charge of the projectile in interaction is the result of a competition between capture of electrons and stripping processes. A direct measurement of the charge value of the projectile inside the solid is not possible, only the charge of an ion emerging the target could be measured. So, only different models which provide very different views of the problem could be used – see for example Lifschitz and Arista's paper for a discussions [12].

The electric charge of the projectile affects both ionisations and nuclear processes. In nuclear interactions, depending on the characteristics of the projectile and target and on the energy, inelastic scattering could be produced, affecting the identity of the nuclei.

In the present paper, the energy losses in ionisation and nuclear reactions are simulated using SRIM package [13], where the effective charge of the projectile is approximated using the scale relation:

$$\frac{Z_{eff}}{Z_{ref,eff}} = \left[\frac{S_{\exp}\left(V, Z_{pr}\right)}{S_{\exp}\left(V, Z_{ref}\right)}\right]^{1/2},$$

where $S_{\exp}\left(V, Z_{pr}\right)$ is the experimental stopping power of the projectile and $S_{\exp}\left(V, Z_{ref}\right)$ is the corresponding power stopping of a reference ion – hydrogen at the same velocity. Details could be found in reference [14]. This estimation of the effective charge extended to stangelets is a first approximation because differences between the binding energies for ordinary ions and strange quark matter are expected.

The effect of the interaction of the incident particle with the electrons of the target is ionisation. For exemplification, in Fig. 1, the energy dependence of the energy loss in ionisation processes in silicon is presented for three ordinary ions: helium, oxygen and silicon and also for the hypothetical strangelets ^{16}He, ^{54}O and ^{350}Si, over an energy range of five decades.

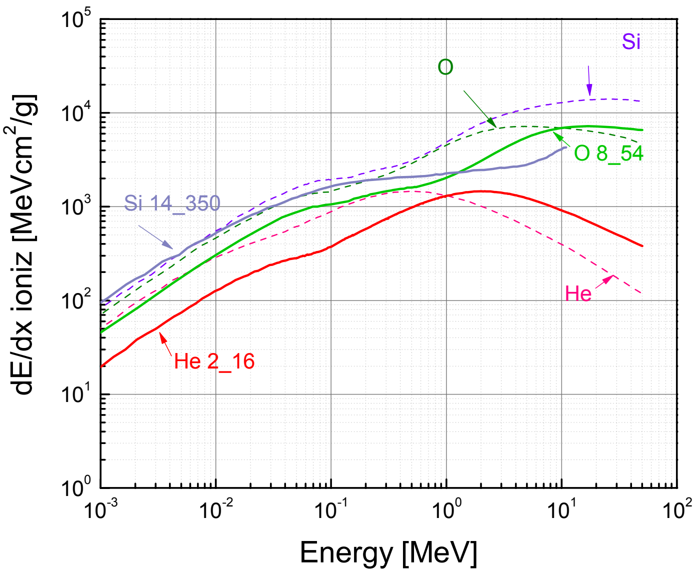

Fig. 1 – Ionization energy loss *versus* energy in silicon for ordinary ions: $^{4}_{2}$He , $^{16}_{8}$O , $^{28}_{14}$Si and for the strangelets: $^{16}_{2}$He , $^{54}_{8}$O , and $^{350}_{14}$Si .

The nuclear interaction between the incident particle and the lattice nuclei produces bulk defects, depending on the nonionising energy loss (NIEL) that is not a directly measurable quantity. The recoil nucleus (or nuclei in the case of inelastic processes) is displaced from the lattice site into interstitial positions. Then, the primary knock-on nucleus, if its energy is large enough, can produce the displacement of a new nucleus, and the process continues as long as the energy of the colliding nucleus is higher than the threshold for atomic displacements.

In Fig. 2, the energy dependence of the energy loss in nuclear processes is presented, in the same material and for the same ions as in Fig. 1.

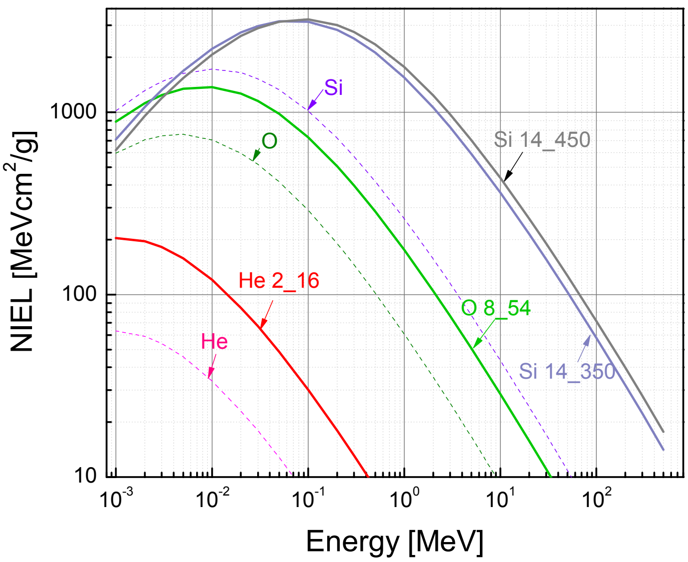

Fig. 2 – Non-ionizing energy loss *versus* energy in silicon for ordinary ions: ${}^{4}_{2}\mathrm{He}$, ${}^{16}_{8}\mathrm{O}$, ${}^{28}_{14}\mathrm{Si}$ and for the strangelets: ${}^{16}_{2}\mathrm{He}$, ${}^{54}_{8}\mathrm{O}$, ${}^{350}_{14}\mathrm{Si}$, and ${}^{450}_{14}\mathrm{Si}$.

As was underlined before, the NIEL is not a measurable quantity, but as a consequence of these processes, structural defects in the target are produced.

The primary mechanism for defect formation due projectile particles in semiconductors is the collision of the incoming particle with the atoms of the crystal, which leads to the departure of an atom to a rather large distance from its original site, i.e., to the formation of separated Frenkel pairs (vacancies and interstitials) as well as of the Si_{FFCD} defect, which is produced [15], and which affects simultaneously more atoms, and which introduces a new type of symmetry in the lattice.

The effect at the device level is an increase of the density of the leakage current. Recently, the authors [16] estimated that, in a silicon detector exposed for two years to a continuous flux of protons from cosmic rays, the passage of one SQM ion (Z=14, A=350) with energy 10 MeV produces a temporary increase in the leakage current density up to about 10^{-4} A/cm^3 from an initial value of 2×10^{-9} A/cm^3.

2.2. NUCLEAR SUB-THRESHOLD REACTIONS

It is well known that nuclear reactions at low energies are suppressed by the Coulomb repulsion between nuclei. Recently, Kuchiev, Altshuler and Flambaum [17] suggested the enhancement of the probability of interaction as a consequence of the "ping-pong" mechanism. A projectile characterized by mass M and velocity V interacts elastically with the target nucleus (with mass m) initiating its motion. If the nucleus target is embedded in condensed matter where heavy environmental nuclei exist, it is possible that the target to be backward scattered and finally re-collide the projectile with an increased velocity. This mechanism is graphically presented in Fig. 3.

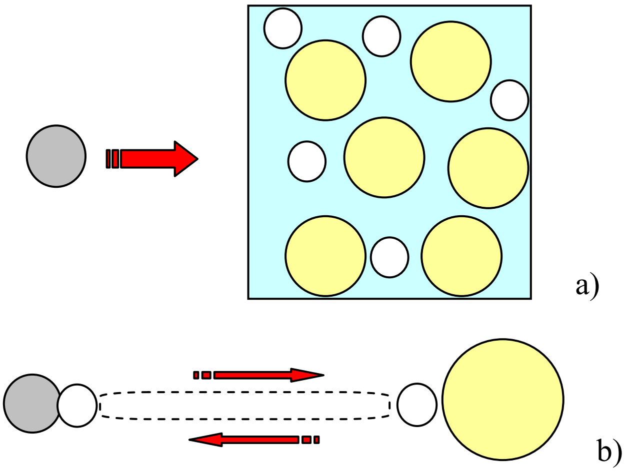

Fig. 3 – "Ping – pong" mechanism: a) collision of the projectile with the target b) elastic scattering projectile – light nucleus of the target (left), elastic scattering on a heavier target nucleus (right), followed by the rescattering and nuclear reaction (left).

In this rescattering mechanism, an enhancement of the probability of nuclear reaction (F) is obtained, in agreement with the equation:

$$F = \frac{1}{a^4}\left(\frac{\mathrm{d}\sigma_{pr-t}}{\mathrm{d}\Omega}\right)\cdot\left(\frac{\mathrm{d}\sigma_{t-env}}{\mathrm{d}\Omega}\right)\cdot\left(\frac{3M-m}{M+m}\right)^3\times\exp\left[\frac{4\pi e^2 Z_{pr} Z_t}{\hbar}\cdot\frac{1}{V}\cdot\frac{M-m}{3M-m}\right].$$

Here, *a* is the distance between the initial location of the target nucleus and the environmental nucleus (in a crystalline structure with two components for example, this is the lattice distance) and the significances of the cross sections are immediate. This mechanism can be a useful tool to discriminate between normal and unusual heavy isotopes (candidates for stranglets).

3. SUMMARY AND POSSIBLE CONCLUSIONS

Ionizing and non-ionizing energy loss dependences on kinetic energy have been calculated for ordinary ions: ${}^{4}_{2}\mathrm{He}$, ${}^{16}_{8}\mathrm{O}$, ${}^{28}_{14}\mathrm{Si}$ and for the strangelet candidates: ${}^{16}_{2}\mathrm{He}$, ${}^{54}_{8}\mathrm{O}$, and ${}^{350}_{14}\mathrm{Si}$ in silicon, in order to use these dependences as a tool to search SQM. The dependence (by the masses of the projectile and of the target and by the velocity of the projectile) of the enhancement of the probability of nuclear interactions at low energies, where Coulomb repulsion suppresses them, by a "ping-pong" mechanism [17], is suggested as a supplementary tool to be used in the search of SQM.

REFERENCES

1. A. R. Bodmer, Phys. Rev. D, **4**, 1601 (1971).
2. E. Witten , Rev. D, **30**, 272–285 (1984).
3. W. J. Swiatecki Phys. Scr., **28**, 349 (1983).
4. V. V. Flambaum, W. R. Johnson, arXiv:0711.1184; Ya. B. Zel'dovich, V. S. Popov, Sov. Phys. Usp., **14**, 672 (1972);
   J. Madsen, Phys.Rev.Lett., **100**, 151102, (2008).
5. C. B. Dover, A. Gal, Nucl. Phys. A, **560**, 559 (1993).
6. E. Farhi, R. L. Jaffe, Phys. Rev. D, **30**, 2379 (1984).
7. Benjamin Monreal, JHEP 02, (2007) 077.
8. T. Saito, et al., Phys. Rev. Lett., **65**, 2094 (1990) ;
   P.B. Price et al., Phys. Rev. D, **18**, 1382 (1978) ;
   M. Ichimura et al., Nuovo Cim. A, **106**, 843 (1993).
9. R. Klingenberg et al., Nucl. Phys. A, **610** 306c (1996).
10. Ke Han, http://home.physics.ucla.edu/calendar/conferences/sqm2006.
11. Yun Zhang, Ru-Keng Su, arXiv:nucl-th/0407016.
12. A. F. Lifschitz, N. R. Arista, Phys. Rev., **A69**, 021902 (2004).
13. *** SRIM – 2006.02 package (www.srim.org)
14. J. F. Ziegler, Nuclear Instruments and Methods, **168**, 17 (1980).
15. S. Goedecker et al, Phys. Rev. Lett., **88**, 235501 (2002);
   I. Lazanu, S. Lazanu, Phys. Scripta, **74**, 201 (2006).
16. S. Lazanu, I. Lazanu, Proc. of the 10th ICATPP Conf., 2007, Como Italy.
17. M. Yu. Kuchiev, B. L. Altshuler and V. V. Flambaum, Phys. Rev. C, **70**, 047601 (2004).