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Title: Specification of radiation quality at the nanometre level.

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I. Summary of Project and Global Objectives

The common aim of this international research group is "research concerning the best possible way of specifying radiation quality for radiobiology and radiation protection by a single physical parameter expressing the track structure". The quoted definition of the group's aim can be easily recognised as an old but urgent target because the application fields of radiation protection and radiotherapy require a physical parameter which can predict its biological efficiency. That aim is difficult because the parameters studied in the past, especially the unrestricted LET and the lineal energy y for a reference volume size of about $1\mu m$, have been proven to be too "rough" to play a role as indicators of track structure at nanometre level. But nanometre is the scale of the critical target of radiation effects, as both molecular biology and radiobiological analysis suggest.

The renewal of this old aim was motivated by new ideas which appeared to describe more adequately the meaningful track parameters at nanometre level (restricted LET and linear primary ionisation) The research on the gas detector physics allows to design microdosimetric instruments able to measure ionisation distributions near the particle track with nanometre resolution and the recent advances in technology suggests the possibility to develop a nano-dosimeter in condensed phase. Modern Monte-Carlo codes, are able to simulate the interaction of particles with the matter at nanometre level. This supports both experimental and theoretical research.

Global objectives of the project concern:

i) to study a gas detector able to measure the ionisation produced by a charged particle in nanometric volumes in order to validate, on experimental bases, the *invariance theorem*;

ii) to study the possibility to manufacture tissue-equivalent gas counters able to simulate nanometric volumes;

iii) to assess the consequences of the assumption of the linear primary ionisation as quality parameter for radiobiology and radioprotection;

iv) to asses the consequences of the assumption of the restricted LET as quality parameter for radiobiology and radioprotection;

v) to investigate the feasibility of an absolute dosimeter based on linear primary ionisation as radiation quality parameter;

vi) to investigate the physical bases of the so called *invariance theorem*;

vii) to calculate, by using Monte Carlo energy transport codes, the ionisation induced in nanometric volumes by charged particles of different energy and charge;

viii) to investigate the possibility to measure radical separation at nanometer level by using ESR technique;

ix) to evaluate existing experimental data and perform new measurements of double differential δ-electron emission cross-sections in heavy ion atom collisions in order to improve our knowledge of the physical phenomena which underlie the radiobiological radiation damage;

x) to improve the Jet Counter experimental set-up to performe nanodosimetric measurements (PECO project).

Calculations performed have confirmed that the fluctuations of the energy deposition in nanometre-sized targets traversed by charged particles are peculiar. Long-range δ-rays escape from very small targets, so that the δ-ray contribution to energy deposition is dominated by short-range δ-rays with energies not larger than about 100 eV. Thus the fluctuations of energy deposition is described by the Poissonian distribution of the number of the primary particle combined with the energy deposition distribution of the low-energy δ-rays. Since the low-energy δ-ray component results to be identical for all types and energies of the primary particle (*invariance theorem*), the absorbed energy fluctuations per traversing particle can be described by only one variable, namely the linear primary ionisation density of the primary particle. Monte Carlo calculations have shown that these findings are valid for a very wide range of proton energies, namely from few hundred of keV to 100 MeV.

As first step to extend the investigation to solid state targets, calculation have been performed to simulate δ-ray emission induced by ions passing thin foils of low-Z material. Calculations have been compared with experimental data. Comparison points out that the error induced by the assumption of gas phase cross-section for simulation of solid state media is tolerable in first order. These findings suggest that the energies fluctuation peculiarities calculated in nanometre gas targets could occur similarly in condensed target.

A well-known representative for linear primary ionisation density is the restricted LET_Δ (with Δ = 100 eV). Therefore calculations have been performed to evaluate the dose-mean values of restricted LET both for the core and the δ-ray halo of charged particle tracks. Moreover radiobiological data have plotted against LET_{100}.

Averaged values of physical track structure (linear primary ionisation density and restricted LET included) and microdose parameters, important e.g. in radiobiology, nuclear medicine, high and low LET radiotherapy, radiochemistry and radiological protection, have been compiled as a ready reference for use in the interpretation of damage mechanisms and for quantifying radiation effects. Moreover, from study of quality parameters active at nanometre level, a new interpretation, based on the primary ionisation density, has been made of the main mechanisms of the radiation action. Validation has been found in the ability to explain unusual radiation effects. A new system of unified dosimetry has been suggested and described quantitatively.

As consequence of these calculated data and phenomenological modelling of the radiation action, a new generation of instruments should be required to assess the radiation risk. However, before of investing in that, it is necessary to validate on experimental bases the calculation data which support the thesis that linear primary ionisation density or LET_{100} are the best parameters to use for the radiation risk assessment.

Gas detectors have been designed and manufactured to investigate experimentally the ionisation distributions in nanometric volumes positioned at variable nanometric distances from a charged particle track. The mean ionisation yield in nanometric volumes around an α-particle track has been measured. This experimental investigation, which we call *track-nanodosimetry*, has been performed with two different detectors and a third detector is under preliminary experimental testing. This technological effort is due to the necessity to minimise the ionisation spectral distortions due to boundary effects, like secondary electron emission from detector walls, and due to the statistical fluctuation in the electronic avalanche inside the counter. The experimental results suggest that it is possible to perform track-nanodosimetry, with an electron counter, with sensitive volumes as small as 10-20 nanometres in diameter. For investigating the ionisation track with smaller volumes, a positive ion counter is necessary.

In the last period of the contract the experimental validation of calculated data at nanometre scale has been enriched by the work performed with a *jet-counter*-based device. This experimental set-up has been shown to be able to measure the mean energy deposition in nanometric gas volumes.

Parallel to ionisation measurements in gas devices, the possibility to investigate the track structure in solid DNA on a nanometre scale has been studied. This approach is based on local electron-spin densities measurements. The experimental tools used have been the ESR and the observation of fast and slow components of the radiophotoluminescence decay.

Finally some basic physics characteristics, on which the future risk assessment monitors will be designed, have been studied both for scintillator and gas devices. For gas devices, both Monte Carlo calculations and experimental investigation has been performed to study the behaviour of electrons in radial electrical fields at low gas pressures. The role of the electrical field gradient has been understood and a simple analytical model, to take it into account, has been proposed. Moreover the so-called non-equilibrium behaviours of the electron swarm near the anode and the cathode walls have been investigated. The findings will allow to design gas devices able to measure properly the ionisation created in nanometric volumes by an external radiation field.