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# CLUSTER ANALYSIS OF TRACK STRUCTURE

## Distributions of Clusters in Tracks of Different Ionizing Radiations

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## Introduction

In the previous paper (Michalik 1991a) one of the possible approaches to the track structure classification based on the K-means algorithm and Monte Carlo track simulation was described. The track is then characterized by the absolute frequency distribution of clusters h(j) which yields the mean number of clusters of order j produced along the track per unit of deposited energy. The cluster order corresponds to the number of ionizations that belong to the same cluster.

All cluster distributions discussed below are computed for the cluster parameter 2 nm. This value of p is characteristic at least for some biological objects (Michalik 1991b). The DNA double helix in B form has diameter 1.52 nm (Arnott and Hukins 1972) which corresponds to a water cylinder with diameter 2.6 nm. There is fairly satisfactory agreement with the p = 2 nm bearing in mind that the analysis of the characteristic value of p was performed only for integer values and that there are very little differences between cluster distributions when p is between 2 and 3 nm. We can suppose that for biological objects, where the DNA is the target, this value of p is also relevant.

Calculations were performed for electrons, photons and heavy ions in the energy ranges important from the practical point of view as well as where the cross sections of individual interaction processes are well known. For every type of particles the properties of the process of interaction with matter that are crucial for the radiation track structure are shortly discussed and the energy dependence of h(j) is listed. Extensive information about the radiation track structure can be found elsewhere (Paretzke 1987).

All the track structure simulations and the cluster K-means analyze were performed on VAX 8350. Each h(j) distribution was calculated for at least one hundred particle tracks with various lengths of the track segment from 0.1 μm to several μm. The track segment length is the result of compromise between the CPU time requirements of the K-means algorithm and the requirement to the track segment to be sufficiently "representative" for a particle with defined initial energy. The distributions are computed after relations described in the previous paper.

**Electrons**

The primary role of electrons in the radiation track structure formation follows from the fact that all energy of primary photons or high energy electrons is transferred to the secondary electrons and then deposited by them in matter. The same is valid for considerable fraction of primary energy of heavy ions and hence also for neutrons. From the point of view of electron interaction with matter for the track structure is important that with increasing electron energy the distance between individual points of energy transfer is increasing and that electrons are subjected to substantial angle scattering, probability of which is increasing with decreasing electron energy.

The frequency distribution of clusters h(j) and the cumulative distribution H(j) versus the electron energy are plotted in Fig.1. The figures show that for $j \geq 3$ the number of clusters decreases with increasing energy and for the electron energy ≥ 10-20 keV there are practically no changes in these distributions. Deviations from this behavior can be observed only for very low energies (100-200 eV) where the frequency of higher order clusters is very low due to a very low probability of origin of a sufficient number of ionizations needed for formation of a given cluster (for example the origin of five ionizations in the track of a 100 eV electron). On the other hand, for $j = 1$ h(j) increases with increasing energy except for the 100 eV electrons, which are very effective in formation of these clusters (up to three times more effective than 200 eV electrons). It reflects a high value of the cross section of elastic scattering of 100 eV electrons. Cluster formation is very strong in the tracks of low energy electrons with energy about 500 eV. A similar conclusion concerning 500 eV electrons was drawn by Paretzke and Schindel (1981) when studying

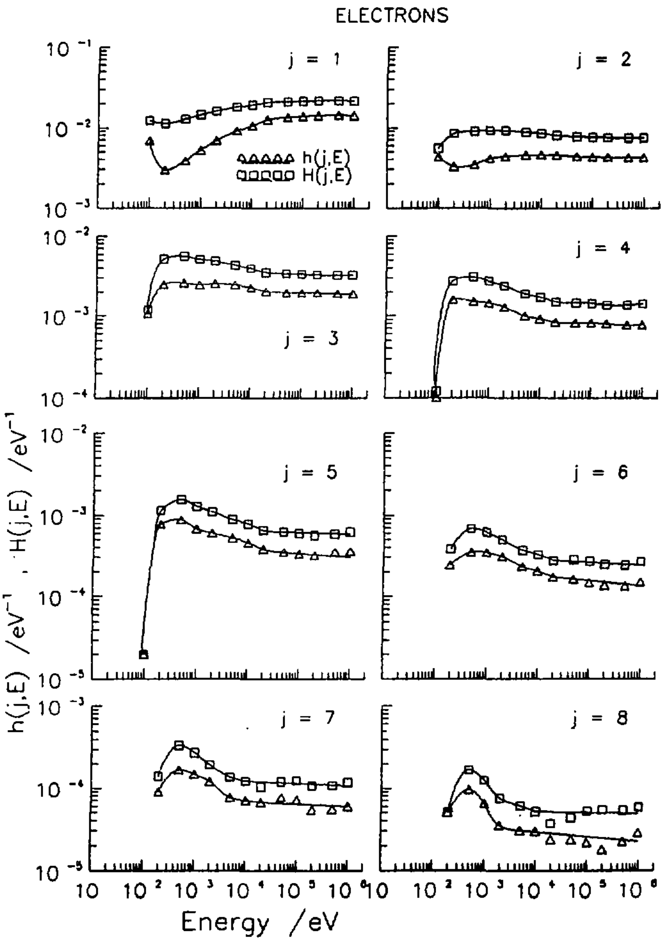


Fig.1. The energy dependence of the absolute frequency distribution of clusters in electron tracks.

distance distributions of nearest neighbors. For 500 eV electrons the probability of formation of a cluster of ionizations in the track is from two to three times higher than for electrons with energy > 10 keV. There are two reasons for the small difference in the cluster distributions for electron energies > 10-20 keV. The mean free path between primary ionizations exceeds the cluster parameter and the frequency of clusters of order one is high, and the formation of higher order clusters is linked predominantly with the secondary low energy electrons, but the fraction of energy deposited by these electrons does not depend strongly on the energy of primary electron.

**Photons**

In the process of interaction with matter a photon transfers its energy to electrons which ionize atoms and molecules along their tracks. Therefore the track generated by a photon is in fact an electron track and the photon track structure is determined by initial energies of electrons ejected by the photon. The photon mean free path between incoherent collisions is as a rule greater than the range of secondary particles and the photon track structure analysis can be reduced to the analysis of the electron track structure.

The distributions h(j) and H(j) are plotted in Fig.2. The differences between corresponding cluster distributions for photon and electron radiation will manifest itself only for low energy photons with initial energy of several keV, where the contribution of low energy Auger electrons to the whole deposited energy is considerable. For higher photon energies the energy contribution of Auger electrons, when photoeffect occurs, or low energy Compton electrons, when Compton scattering takes place, is negligible and the h(j) of higher energy photons is determined by h(j) of high energy electrons. But for high energy electrons there are nearly no differences in their ability to form clusters of ionizations and therefore there will be no differences among h(j) of these photons.

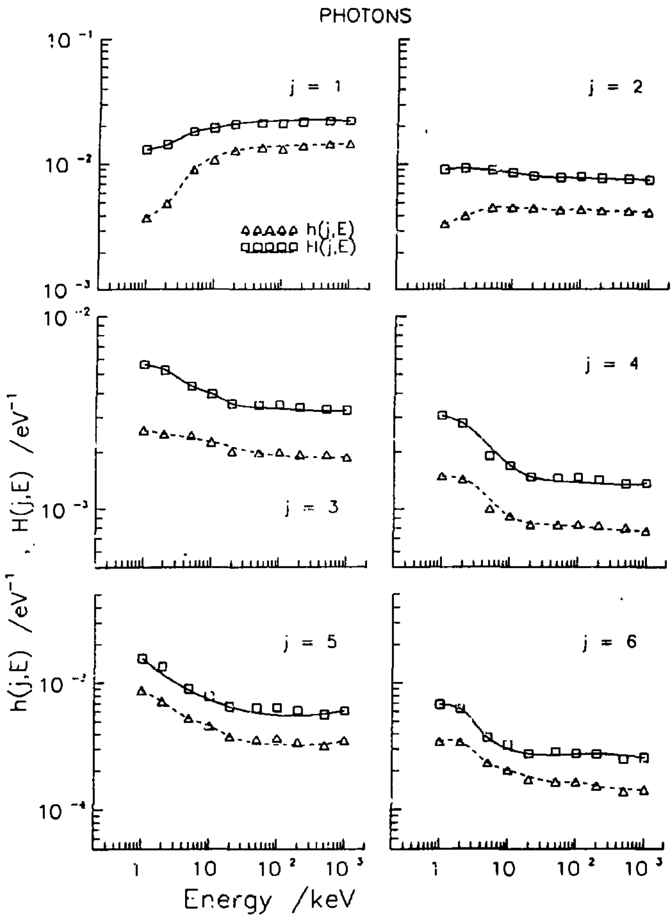


Fig.2. The energy dependence of the absolute frequency distribution of clusters in photon tracks.

There are now many radiobiological data concerning biological effects of ultrasoft X-rays which among others shows the following (Goodhead 1990): a) ultrasoft X-rays are more effective than equal doses of hard X-rays or $\gamma$ rays. b) The RBE for inactivation decreases with increasing ultrasoft X-rays energy. c) very local isolated events are alone sufficient to produce complete permanent biological damage. Comparing the above-mentioned experimental facts with the curves in Fig.1 and Fig.2. one clearly sees that energy dependence of $H(j)$ for $j = 1$ and $j = 2$ contradicts the experimental data. If one takes the threshold concept of radiation action, then only formation of cluster of $j \geq 3$ can be considered as biologically critical property of radiation for lethal effect.

**Heavy ions**

For heavy ions with energy 0.5-100 MeV/u one can state that 65% - 75% of energy loss is transferred to the secondary electrons which witnesses the significance of secondary electrons in the analysis of heavy ion track structures as well. The fraction of energy deposited along or very near to the ion path falls down with increasing initial energy of the particle. The probability of ion interaction with molecules is proportional to the square of the ion charge and hence at the same particle velocity the number of secondary electrons emitted per track length unit of primary particle is higher for a particle with higher Z, and the mean free path for the particle with higher Z will be shorter. The track structure of heavy ions can also be influenced by two processes, the electron capture of a target molecule or, if ion is not fully stripped of its electrons, it can lose its own electrons and capture electrons of target molecules. The heavy ion tracks are straight, because their greater mass is the cause of a much lower probability of elastic scattering.

In Fig.3. and Fig.4. there are distributions $h(j)$ and $H(j)$ for protons and $\alpha$-particles respectively. As figures show, there is only small qualitative difference in energy

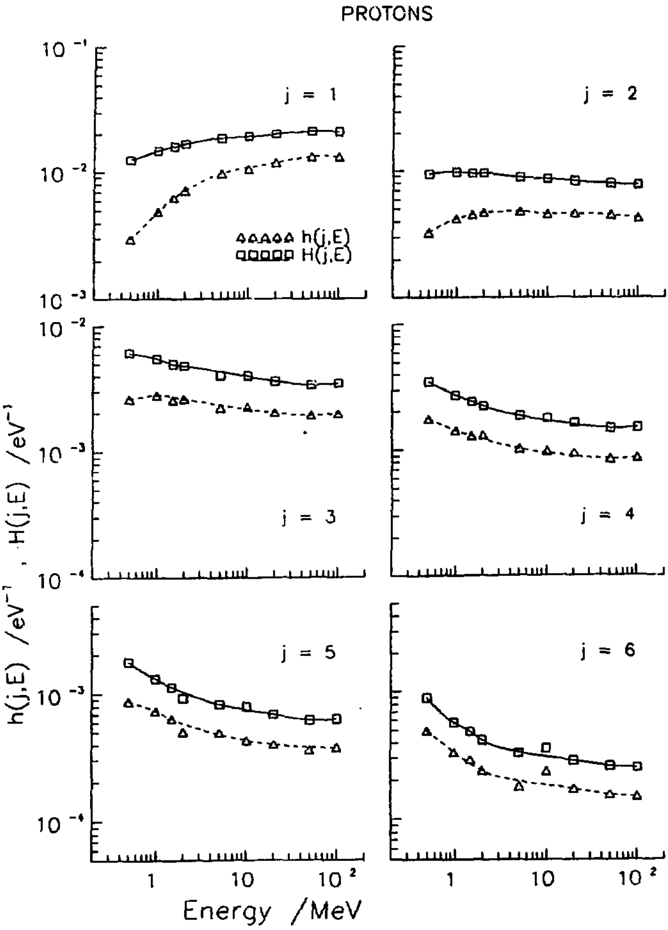


Fig.3. The energy dependence of the absolute frequency distribution of clusters in proton tracks.

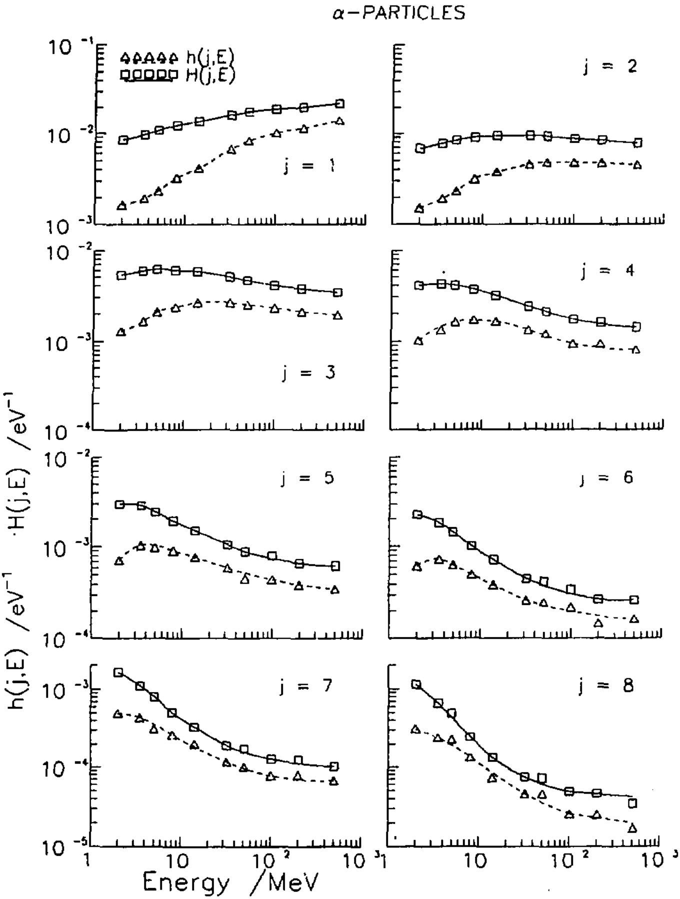


Fig.4. The energy dependence of the absolute frequency distribution of clusters in α-particle tracks.

dependence of cluster distributions between electrons and heavy ions. For $\alpha$-particles a maximum can be observed for some values of j and it is connected with the shift of the maximum to higher order clusters in the distributions h(j) for low particle energy, when the density of primary ionization is high.

When studying the effects of heavy ions the approximation of the track divided into the track core and penumbra is frequently used. The track core is the inner part of the track adjacent to the geometric path. When estimating the initial radius of the core most authors use the Bohr adiabatic criterium. For nonrelativistic velocities when the screening effect of matter is weak, the radius of a core is given by $r_c = \hbar v/2\varepsilon_1$, where v is the velocity of the charged particle, $\varepsilon_1$ is the lowest electronic transition energy, and $\hbar = h/2\pi$ is the modified Planck's constant. The core contains all glancing collisional losses and the energy deposited by electrons traversing the core region and by low energy electrons which are stopped completely in this region. The penumbra contains the energy deposited outside the core. What is the difference in the spatial patterns of the energy deposited in the track core and in the penumbra? Fig.5. shows the dependence of the mean cluster size in the core and in the penumbra on the initial particle energy for protons and $\alpha$-particles. The mean cluster size in the penumbra $\bar{j}_p$ is independent of both the ion energy and the ion type and when comparing the whole cluster distributions, one finds very small differences. The value of $\bar{j}_p$ corresponds to the mean cluster size for low energy electrons with energy 1.5-2 keV. In the track core the mean cluster size $\bar{j}_c$ changes with energy in accordance with the energy dependence of the density of primary ionizations. Energy independence of the $\bar{j}_p$ indicates the fact that the information about the radiation quality of heavy ions is contained in the radiation parameters directly connected with the primary ionizations. From this point of view the restricted linear energy transfer $L_\Delta$ with a very low value of cut-off energy $\Delta$ is this quality parameter of radia-

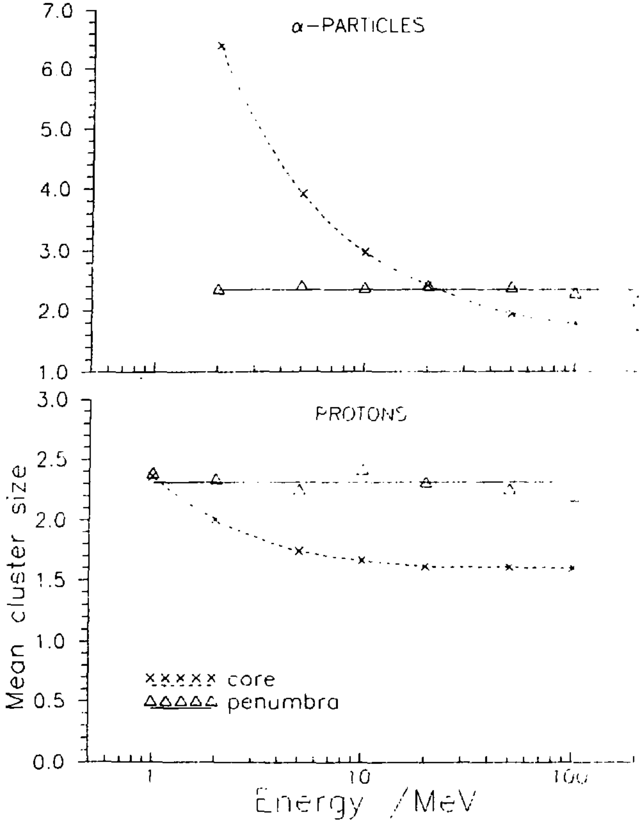


Fig.5. The energy dependence of the mean cluster size in the penumbra and the track core for protons and α-particles.

tion reflecting fluctuations of energy deposition in nanometer regions. This result is in agreement with recent works discussing $L_\Delta$ as a radiation quality parameter (Bartels and Harder 1990, Hahn *et al* 1990).

## Conclusion

Different types of ionizing radiations (100 eV - 1 MeV electrons, 1 keV - 1 MeV photons, 1 MeV/u - 200 MeV/u heavy ions) have been studied with respect to their ability to form clusters of ionizations along the radiation tracks. For all types of radiation listed above we can summarize the following: a) the probability of origin of clusters of order one in tracks increases with an increase in particle energy up to the plateau region. b) The probability of origin of clusters of order two depends very little on the particle energy. c) For clusters of orders higher or equal to three starting from some energy a decrease in the occurrence of these clusters with increasing particle energy is observed. d) In the region of high primary energies of particles, where the density of ionizations is low, there is practically no difference in the cluster distributions. The same conclusions are valid for the cumulative distributions.

Providing a threshold model of radiation action, i.e. that the cluster of the order $\geq j$ leads to the inactivation of the cell, then the above conclusions result in the following consequences: a) a cluster of order one cannot give the RBE values greater than one. b) A cluster of two ionizations is not sufficient to yield a distinct maximum in the RBE-LET dependence as well. c) The threshold cluster size must be $\geq 3$. d) A plateau in the region of low LET values in the RBE-LET dependence can be explained very simply. In this LET region there is very small difference in the corresponding cluster distributions and hence the physical stage of radiation action is the same. Under the same conditions it will lead to the same final effects.

The cluster analysis of the heavy ion track structure also shows that the restricted linear energy transfer with a very low value of the cut-off energy is good single parameter of the radiation quality.

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