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TRACK STRUCTURE AND OVERKILL

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Структура трека и эффект насыщения

Последние экспериментальные данные показывают, что зависимость ОБЭ от ЛПЭ является более сложной, чем предполагалось раньше, и что нужно искать объяснения на физическом и физико-химическом уровнях. Важную роль в этих процессах играет сердцевина трека и происходящие в ней изменения. Формирование индивидуальных ниспадающих линий из совместной зависимости ОБЭ от ЛПЭ соответствует превышению некоторого критического уровня концентрации энергии в сердцевине трека. Из-за изменений в сердцевине трека происходит уменьшение прямого и косвенного воздействия. Эти факты могут объяснить формирование индивидуальных ниспадающих линий из совместной зависимости ОБЭ от ЛПЭ без предпосылки о насыщении повреждений.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Track Structure and Overkill

Recent experimental results showed that RBE dependence on LET has a more complex structure than was earlier supposed and that we have to look for explanation at the physical and physico-chemical level. The track core and changes within it plays an important role in these processes. Formation of individual hooks of decreasing branches from a common RBE-LET curve corresponds to extention of the track core energy concentration beyond some limit value. Due to changes in the track core there is a decrease in the direct as well as indirect effect. These facts can explain the hook formation without the overkill presumption.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1989

INTRODUCTION

There are many experimental results concerning the dependence of relative biological effectiveness (RBE) on linear energy transfer (LET) measured for different biological objects and endpoints. The measurements using light ions [1-3] showed the RBE dependence on LET to be increasing with LET up to a local maximum at 100 keV/μm followed by a decrease for higher LET values. This dependence is very similar for different biological objects and endpoints.

There is the following interpretation of obtained results : Low LET radiation at low doses produces sublethal damages at great distances from one another, they interact with a small probability and are easily repairable. For higher doses there is an increasing number of sublethal damages and lethal lesions can occur with greater probability. For higher LET there are smaller distances between sublethal damages and the interaction probability increases, radiation becomes more effective and reaches an effective maximum at some LET value (about 100 keV/μm) where the number of damages extends beyond the amount necessary to produce the endpoint. Further increase of LET also evoke increase of energy deposition fluctuation in biological targets. It means that the RBE dependence on LET will decrease for high LET and the action cross section dependence on LET will display a plateau in the action cross section value corresponding to the size of the geometrical cross section of the critical target.

Recent experiments [4] using a wide variety of particles and energies showed that the RBE (or σ) dependence on LET is more complex (Fig.1). For heavier ions the maximum of the effectiveness is shifted to 200 keV/μm and for greater LET values the RBE curves form individual "hooks" of decreasing branches from a common RBE-LET curve. This structure is also observed for the inactivation of yeast cells and bacteria spores [4] and for the mutation induction in bacteria spores [5] and yeast cells [6]. It was shown [7] that we can exclude in interpretation of hooks the case of overproduction of biological damages, since a similar dependence on LET was observed for molecular effects such as DNA breaks and so we have to look for the answer at the physical and chemical level.

Recently it has been shown [8] that the dominant mechanism for reproductive death in mammalian cells is determined by the matching of the mean free path between ionizations to the strand separation in double stranded DNA. Electrons have greatly reduced intrinsic efficiencies of action when compared with heavier particles because they can reach the requisite specific primary ionization only at very low energies when they undergo large range straggling. Besides heavy ion induced δ electrons, the track core plays an important role in explanation of the RBE dependence on LET since a large fraction of energy is deposited in it.

TRACK CORE ENERGY CONCENTRATION CALCULATION

We can imagine a particle track as a compound of track core and individual δ electrons. The track is a cylinder with an axis identical to the ion's geometrical path and with a radius r_{core}. The radius r_{core} can be defined as an effective impact parameter value for which the primary particle is able to excite a molecule to the state with the smallest energy transfer $\hbar\omega_{01}$. Than the track core radius [9] is

$$r_{core} = \frac{\hbar v}{\omega_{01}} , \qquad (1)$$

where v is the speed of the particle. Further we can express the part of the primary particle energy deposition in the track core. Of the total stopping power, the fraction F_δ, transferred to the kinetic energy of δ rays with the range greater than r_{core} is

$$F_\delta = \int_{E_{min}}^{E_{max}} E \, d\sigma(E) \Big/ L_\infty , \qquad (2)$$

where $d\sigma(E)$ is the differential cross section for ejection of δ rays of energy E. In calculation we used the Rutherford formula for the collision of an ion with an electron

$$\frac{d\sigma}{dE} = \frac{2\pi Z^{*2} e^4}{mc^2\beta^2} \frac{1}{E^2} \qquad (3)$$

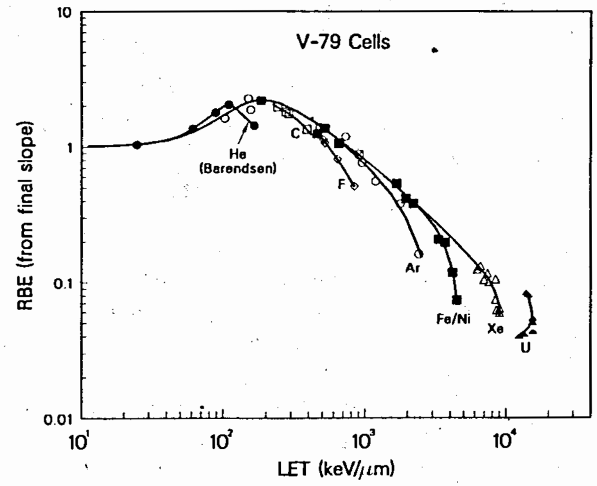

Fig.1 RBE values for inactivation by different ions (G. Kraft et al. 1989).

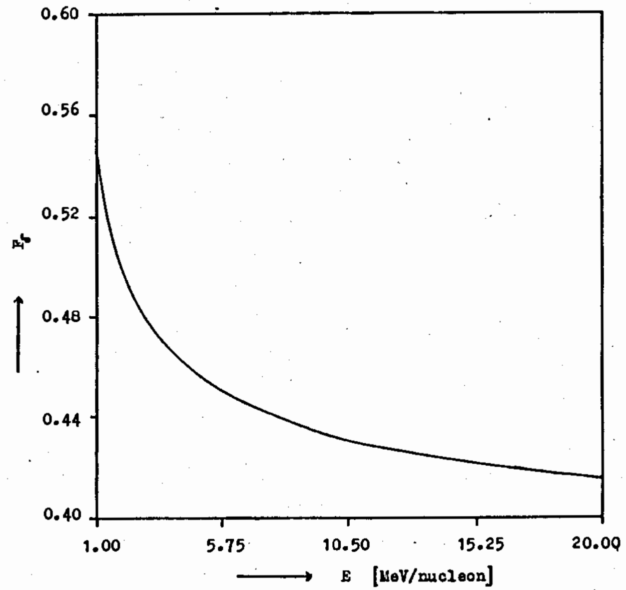

Fig.2 Fraction of the total stopping power transferred to the kinetic energy of δ rays with range greater than r_{core} as a function of the ion energy.

and the linear energy transfer L_∞ is given by the Bethe expression for the stopping power of uniform medium for heavy charged particles

$$-\frac{dE}{dx} = \frac{4\pi Z^{*2} e^4 N}{mc^2\beta^2}\left[\ln\frac{2mc^2\beta^2}{I(1-\beta^2)} - \beta^2\right], \qquad (4)$$

where $Z^* = Z\left[1-\exp(-125\beta Z^{-2/3})\right]$.

E_{max} is the maximum energy transfer in a single collision of the heavy charged particle with an atomic electron and E_{min} is the energy of the electron with the range equal to r_{core}. E_{min} can be derived from the semiempirical relation /10/ between the electron range and its energy. The F_δ dependence on the heavy ion energy for water is in Fig.2. If F_δ, L_∞ and r_{core} are known, we can calculate the track core energy concentration n_{core}

$$n_{core} = \left[\frac{L_\infty(1-F_\delta)}{\pi r_{core}^2}\right]. \qquad (5)$$

DISCUSSION

Dependence of the track core energy concentration n_{core} on the ion energy and on LET is in Fig.3 and Fig.4 respectively. Comparing Fig.1 and Fig.4 we can conclude that RBE-LET hooks formation corresponds to the situation, when the track core energy concentration exceeds some limit value between 1-3 $eVnm^{-3}$.

Apparently such energy concentrations give rise to a high density of ionizations and excitations and originating radicals, ions and electrons are very near each other and they can recombine with a high probability. This is confirmed by the experimental results giving low yields of free radicals and higher yields of molecular products for high LET values. According to the ion spike model /11/, radiation deffects of heavy ions in condensed matter occur as a result of Coulomb repulsion of ionized atoms. In the case of effective recombination there will be considerable suppresion of this effect. The hook formation corresponds to the end of the particle track where changes in the track core and in the angular and energy distribution of heavy ion induced δ electrons occur. Due to these changes there can be a decrease of the direct effect (recombination of a positive ion with an electron) and of

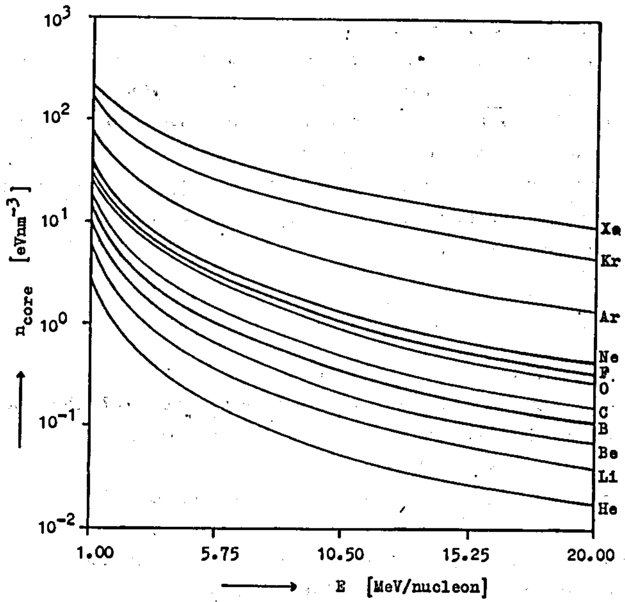

Fig.3 Track core energy concentration as a function of the ion energy.

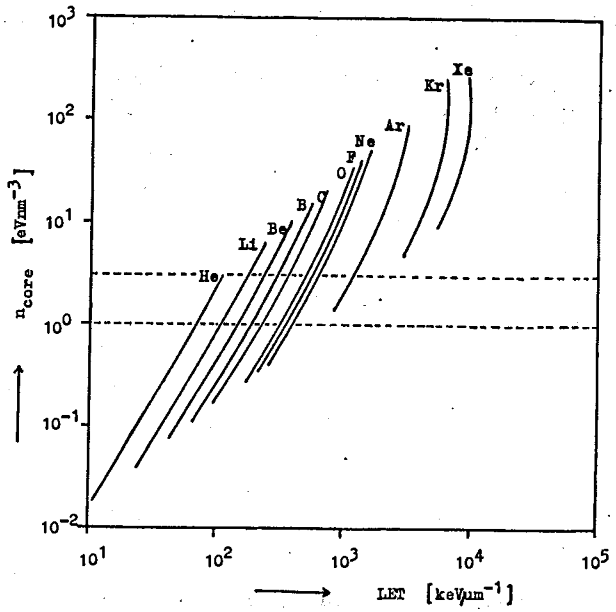

Fig.4 Track core energy concentration as a function of LET. Between the dashed lines there are n_{core} values corresponding to hook formation.

indirect effect (recombination of free radicals). If this recombination mechanism works we can explain the hook formation without the overkill presumption. But in the explanation of the common RBE-LET curve we must retain the overkill model. The results from heavy ions biological experiments are predominantly obtained using particles with low Z and in the LET range up to hundreds keV/μm. For such particles n_{core} values are too small for effective recombination.

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