APPLICATIONS OF MEASUREMENTS AND INSTRUMENTATION

David A.Bradley
School of Physics, University of Exeter, United Kingdom

Yuri M.Tsipenyuk
P.L.Kapitza Institute for Physical Problems, Russian Academy of Sciences Moscow, Russia

Keywords: radiation processing, non-destructive testing, radiation damages, interaction of laser radiation with matter, thermal plasma, ultrasound, radiation treatment, Josephson effects, superconductors, eddy current, fluorescence.

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Summary

This chapter reviews a number of areas in which notable progress has been made in applications of physical measurements and instrumentation. The intent of the chapter is to demonstrate the significant impact of these initiatives, giving rise to new perspectives in a number of fields of endeavor. Included in the review are coverage of the basics of

radiation processing, radiation therapy and radiation biology, thermal plasma processing, use of laser light in medicine and industry, superconducting magnetometers in medicine, and methods of non-destructive testing.

1. Introduction

Methods, procedures and measuring techniques developed by physicists have become powerful tools for use in a great many interdisciplinary research areas, studies of the environment being just one of the many such important examples of where progress can be noted. These developments have revolutionized technology and provided the basis for improving the human condition itself. They also continue to lead to the identification of a great many novel possibilities for applications.

Of this process, Walter Brattain, one of the discoverers of the transistor, wrote:
'The transistor came about because fundamental knowledge had developed to a stage where human minds could understand phenomena that had been observed for a long time. In the case of a device of such consequence to technology, it is noteworthy that a breakthrough came from work dedicated to the understanding of fundamental physical phenomena, rather that the cut-and-try method of producing a useful device.'

Here we might also recollect that the cathode ray tube was invented at the end of the 19th century for the purpose of measuring the charge and mass of the electron. This very same cathode tube is also the main element of television set and certainly it would be hard to imagine modern life without television sets or monitors.

Less than 1 % of the world's accelerators are presently being used for particle physics research, this being the purpose for which they were created and perfected. The rest are used in medical applications and commercial processes involving markets of tens of billions of US dollars.

Over forty laboratories throughout the world currently operate electron or positron storage rings as sources of synchrotron (electromagnetic) radiation, with more such machines now being built. These machines, which provide beams millions of times more intense than were available forty years ago, are used in research in solid state physics, chemistry, biology, medicine, etc. They are also beginning to demonstrate potential for mass scanning of heart disease, and are used commercially in the production of new semiconductor chips with circuit elements packed to a density of 1000 times more than previously attainable, promising faster, more powerful, more compact and cheaper electronics.

Free electron lasers (FEL's) use accelerator techniques to produce undreamed of intensities of radiation. These research instruments are being used for similar purposes as synchrotron radiation sources, although they operate at a longer range of wavelengths (from millimeter and submillimeter wavelengths up to the so-called soft X-ray region).

Accelerators are now being used to produce radioisotopes for medical diagnosis. Several types of accelerated particle beams are also being used directly in diagnosis (X-rays), and radiotherapy, where electrons and electron-generated gamma rays, neutrons,

protons, pions and heavy ions have been exploited for their different biological effects.

Accelerators are now being used in diverse locations around the world to implant ions in the production of integrated circuit chips, as well as for the production of alloys involving traces of rare metals. Accelerated particle beams are also used in food processing to eradicate bacteria, leading to extended shelf-life. Such radiation is also used to improve the mechanical properties of materials, including plastics. The wide spread use of nuclear radiation for non-destructive testing is also well known.

In a chapter of this type it is also important to make considerable mention of the role of lasers in the development of science and technology. The unique properties of laser light enables biologists to examine single protein molecules attached to the inner membrane of a red blood cell. Physicists are able to levitate millions of sodium atoms in stainless-steel containers and release them simultaneously in fountains of light. Chemists can observe a single hydrogen atom pulling an oxygen atom away from a CO_2 molecule. Femtosecond lasers can freeze the motion of atoms and move them around at will. A technique refered to as 'optical molasses' uses laser light to create electromagnetic forces that can slow down supersonic atoms. The resulting controlled atoms, observed in both free fall and oscillating motions, enable the measurement of gravitational forces with greatly increased accuracy over previous techniques and the development of new generations of atomic clocks. Lasers are also an essential part of an atomic force microscope, a remarkable 'sensor' that offers a quick and accurate method foe measuring the atomic details of a surface.

For a chapter of this type, which seeks to review a broad spectrum of applications, it is neither possible nor suitable for us to want to cover all possible applications of physical methods and instrumentation. We shall instead attempt to provide more detailed coverage of several important areas of industrial and other applications, being those in which physical measurements and instrumentation have lead to notable significant progress.

2. Radiation Physics

2.1. Radiation Effects

It is well known that in solids, live cells or liquids, nuclear particles are capable of destroying the structure of these substances. As an instance, damage to structural materials is practically inevitable within the hostile environments created by nuclear reactors and accelerators. More desirably, these same sources can be made to purposefully initiate chemical reactions or to effect particular changes in the properties of substances in a controlled manner. For human protection from nuclear radiations as well as for their diagnostic and therapeutic applications it is necessary to have detailed knowledge of the consequences of their influence on living organisms. All of these topics outlined above are related to the field of radiation physics.

2.1.1.Radiation Units

To estimate quantitatively what affect sources of nuclear radiations might have and the

degree to which such influence might be controlled, special units of activity and dose have been introduced. In 1981 the international systems of units (SI) was adopted on a fairly worldwide basis. Non-SI units remain in common use in some countries, most notably the USA, and we therefore provide an account of SI and non-SI units and the relationships between the respective quantities.

The unit of radionuclide activity is the *becquerel* (Bq), this equating to one nuclear disintegration per second (or more loosely, one decay per second). The non-SI unit of activity is the *curie* (Ci), a unit enjoying widespread usage before the advent of SI units. One curie of activity equals 3.7×10^{10} decays per second, and hence

1Ci= 3.7×10^{10} Bq   (1a)
or conversely,
1 Bq = 2.7×10^{-11} Ci   (1b)

The absorbed dose of a radiation, D, is the ratio of the average energy $d\overline{E}$ transferred by the ionizing radiation to a volume element of the substance to the mass dm of the substance in the volume

$$D = \frac{d\overline{E}}{dm}$$

(2)

The unit of the absorbed dose is the *gray* (Gy). The gray corresponds to the deposition of one joule of energy of any kind of ionizing radiation in 1 kg of the irradiated substance. The old, non-SI unit of absorbed dose is the rad (<u>r</u>adiation <u>a</u>bsorbed <u>d</u>ose), where 1 rad = 10^{-2} J kg^{-1} and therefore

1 Gy = 1 J kg^{-1} = 100 rad   (3a)
or conversely,
1 rad = 0.01 J kg^{-1} (3b)

The notion of absorbed dose is useful, as in the energy region up to 10 MeV the main effects owing to radiation are proportional to the deposited energy and are almost independent on the type of nuclear radiation. It is necessary to emphasize here that the mechanism of energy deposition relates to ionization losses of the primary radiations and to the secondary particles which are produced by nuclear radiations in their path through a substance.

Since dose per unit path length of a given medium can be deposited in greater or lesser amounts, according to the type of radiation and its capacity for ionization there is need to account for this in quantitative estimation of the biological effect. The notion of *equivalent dose*, D_{eq}, is introduced as the product of the absorbed dose D in the biological tissue and a quality factor, Q_i, related to the dose deposition pattern:

$D_{eq} = D\, Q_i$ (4)

For mixed radiation:

$D_{eq} = \sum_i D_i\, Q_i$ (5)

where the index i relates to the various radiation components of different quality. The values of Q for different particles are given in Table 1.

Type of radiation	Q

X-ray and gamma-radiation	1
Electrons, positrons, beta-radiation	1
Protons with energy less 10 MeV	10
Thermal neutrons	2.3
Neutrons with energy less 20 keV but >0.025 eV	3
Neutrons with energy 0.1-10 MeV	10
Alpha-radiation with energy less 10 MeV	20
Heavy recoil nuclei	20

Table 1. Values of *Q* for different radiations

The unit of the equivalent dose in the SI system of units is the *sievert* (Sv), where:
$1\ Sv = 1\ Gy/Q$ (6)
In the non-SI system of units the equivalent dose is the rem (roentgen equivalent man), where 1 rem = 1 rad/Q, and therefore
$1\ Sv = 100\ rem$ (7a)
or conversely,
$1\ rem = 0.01\ Sv$ (7b)

The exposure resulting from photon irradiation is the ratio of the total charge *dQ* of all ions of the same sign produced in an air when all electrons and positrons created by photons in the air volume element of mass *dm* are completely stopped in that mass
$D_{ex} = dQ/dm$ (8)

Exposure is measured in C kg^{-1} this being connected with the older non-SI unit – the roentgen – by the relation:
$1\ C\ kg^{-1} = 3.88 \times 10^3\ R$ (9a)
or conversely,
$1R = 2.58 \times 10^{-4}\ C\ kg^{-1}$ (9b)

To estimate the influence on a medium of indirect ionizing radiation, say for instance neutrons, the notation *kerma* is used (kerma is an acronym of the words *kinetic energy released in the material*). The kerma, *K*, is the ratio of the sum of the primary kinetic energy *dT* of all charged particles produced under the influence of the indirectly ionizing radiation in an elementary volume of a given substance to the mass *dm* of that substance
$K = dT/dm,$ (10)
In dosimetry special substances are used: air for photon radiation, biological tissue for indirectly ionizing radiation used in biology and medicine, and any suitable material in investigation of radiative effects. The unit of kerma is the same as for absorbed dose.
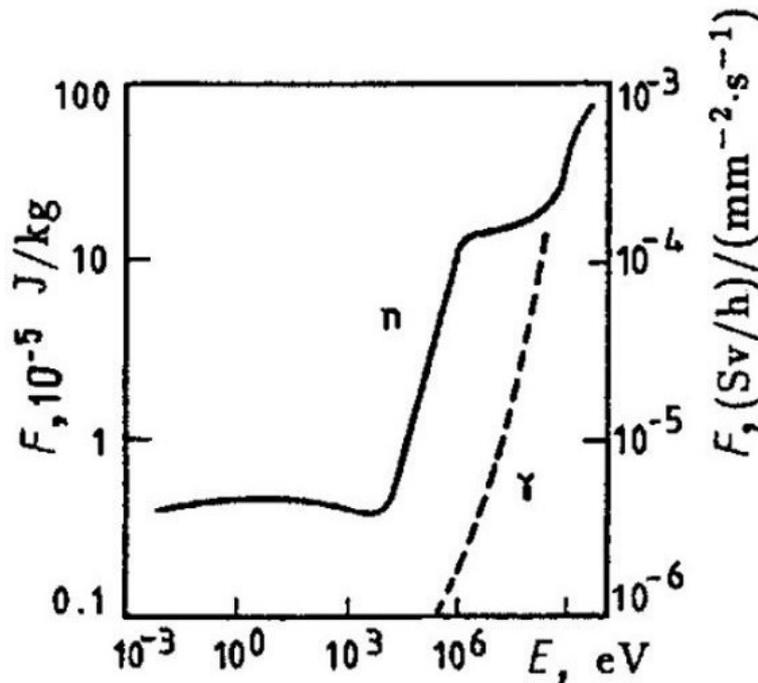
Figure 1. Conversion from a particle flux per unit time into a dose rate for neutrons and gamma-rays.

(see *Accelerators and reactors*)

In practice a radiation source is often characterized by the flux of particles it creates. The radiation dose equivalent for a given particle flux varies both with the particle type and their energy. Figure 1 shows the conversion from a real particle flux per unit time into a dose rate in Sv h^{-1}. One sievert is a very large equivalent dose, in particular a few sievert of whole body irradiation can kill a human being, and in radiation protection dosimetry we therefore more usually deal with milli-sievert levels of equivalent dose, that is about equal to our mean annual dose from natural sources of irradiation. We are also often interested in the rate at which dose is incurred, and for this we shall use mSv h^{-1}.

2.2. Damage Production in Solids

Radiation damage in solids results from the production of atomic defects in the material. The first stage in such a process concerns the interaction of the bombarding particle with the crystal lattice, followed by the appearance in the irradiated material of a single lattice defect – a vacancy and an implanted atom or interstitial, i.e. an atom between lattice sites. Each such pair, composed of the vacancy and an atom in the interstice, is called a Frenkel defect, or Frenkel pair (see Figure 2).

The constituents of the pair can also occur separately. As an example, vacancies in equilibrium with the lattice vibrations can be produced in the lattice as a result of one of a number of sources: from grain boundaries, dislocations, micropores and so on. Vacancies as well as interstitial atoms can also occur independently each from other during the motion and mutual intersection of dislocations under plastic deformation. Conversely, a mutual origin to the Frenkel pair inside a regular crystal lattice will only

result from radiation damage. As such, investigation of the dependence of solid-state features on this major means of creating damage to the structure of the ideal solid is uniquely possible through use of this new experimental tool – viz. the influence of radiation on substance.
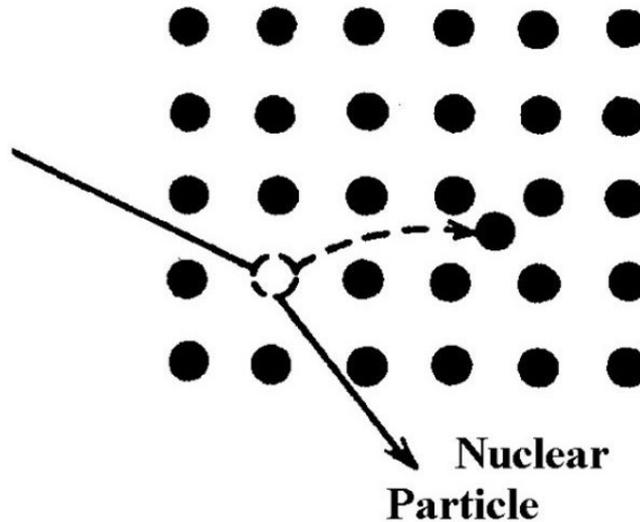

Figure 2. The scheme of the creation of the Frenkel pair – a vacancy and an atom in an interstice

To knock an atom out of its equilibrium position in the crystal lattice it is necessary to transfer to it an energy greater than some particular threshold value, E_d, this being the difference between the binding energy in the normal location, i.e. at the equilibrium site, and in an interstice. The value E_d is of the order of tens of electronvolts, and, in the example cases of Cu, Fe and diamond is equal to 22 eV, 24 eV and 80 eV respectively. As a result of recoil, in elastic collisions an incoming particle cannot transfer to the atom its total energy. In most cases the mass of incoming particle is much less the mass of an atom, and therefore to knock an atom out of a lattice site the energy of the particle has to be much more than E_d. Figure 3 shows the minimum energy of alpha-particles, electrons and gamma-quanta needed to allow different atoms to escape binding to the lattice, calculated assuming that for all crystals $E_d = 25$ eV.
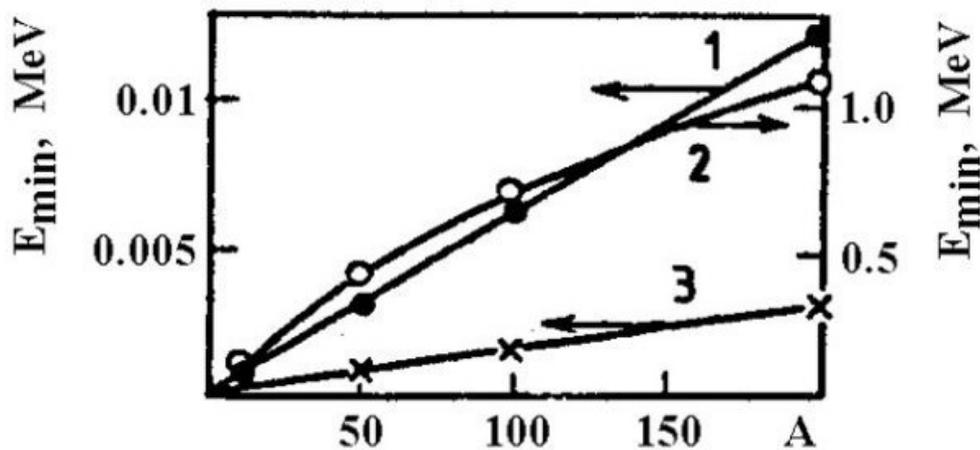

Figure 3. Minimum energy for the displacement of different atoms ($E_d = 25$ eV): 1 – neutrons and protons, 2 – electrons and gamma-quanta, 3 – alpha-particles.

If the energy of the displaced atom considerably exceeds E_d it is possible that in turn this can knock another atom from the lattice, and in such a way one primary collision can displace several atoms in the crystal, creating secondary, tertiary and other groups of displaced atoms. In the limit the cascade caused by the primary atom can be considered as a complex reconstruction of the crystal lattice, referred to as the peak of displacement. The origin of the displacement peak and its subsequent relaxation leads to considerable motion of atoms, resulting in annihilation of many point defects and also producing more complex defects, in particular dislocation loops.

Below we consider various processes for the dislodging of atoms from lattice sites, brought about using different types of irradiation.

Photons.

There are three processes of atomic displacement caused by gamma-quanta:
1. Electrons ejected by photons can possess sufficient energy to displace atoms in a solid. Such fast electrons (~ 1 MeV) can result from Compton scattering, photoeffect or pair production.
2. Displacements can be caused by recoil nuclei which result from photonuclear reactions (such reactions occur at energies of more than 10 -15 MeV), being for the most part (γ,n) and (γ,p) reactions.
3. The third process, which concerns a more limited group of crystals, especially alkali-halides, occurs when the quantum energy is not sufficient to create atomic displacement by any process of direct collisions. This situation takes place in the case of X-rays. The incoming X-rays excite electrons from inner shells of a light atom and then the Auger cascade follows with a rather high probability. The primary energy (of the order of some several keV) is used in local electron excitation, and this occurs during a very short time (~10^{-15} s) following irradiation. Atomic reconstruction, which leads to appearance of the displaced atom, is due to an excess of positive charge that accumulates in a small volume, i.e. the electrostatic field of the lattice shifts a positive ion into an interstice. Owing to the high penetrability of γ-quanta lattice damage occurs uniformly throughout the volume of the solid.

Neutrons.

A neutron in a direct collision with an atomic nucleus can transfer to the atomic nucleus sufficient energy for its immediate displacement. The transferred energy may also be sufficient to create subsequent displacements, the atomic nucleus eventually slowing down until it is also stopped in the lattice. Another process of neutron mediated atomic displacement concerns the initiation of nuclear reactions, the products of which are the cause of displacement. Examples of such reactions include: ^{10}B (n,α) ^{7}Li, ^{57}Fe (n,γ) ^{58}Fe, ^{238}U (n,f). As for the case of gamma-quanta fast neutron damage will also be uniformly spread over the object being irradiated, even to the extent that this concerns large samples, the neutron mean free path between collisions often being of the order of several centimeters.

Electrons

High-energy electrons with energy ~1 MeV cause atomic displacements by direct Coulomb interaction with the nucleus of a solid. Given that nuclear mass is ~ 2000 greater than an electron mass this collision can only lead to a change in the direction of electron momentum. One disadvantage of electron bombardment is the rapid slowing down of electrons as a result of significant energy exchange with the electrons of the solid, i.e. in high value of ionization loss. As a consequence, the radiation damage is only uniform in thin samples of up to some millimeters thick. Naturally, high-energy electrons will be able to cause more uniformly distributed damage in somewhat thicker samples. In summary, the number of displaced atoms, $\overline{n(E_0)}$ depends on the electron energy and the mass of atom.

Ions

In its path within a solid a fast atom will at first lose a fraction of its complement of electrons, becoming a multi-charged ion as a result of this process. During this part of its passage through a medium the main cause of energy loss is electron excitation, although sometimes the moving atom can also directly interact with lattice atoms. With the energy of the resultant ion now decreased, its propensity for capture of atomic electrons increases and simultaneously the rate of its energy loss for electron excitation decreases. Finally, the moving ion will be neutralized and its energy will then be mainly spent in collisions with atoms of the irradiated medium, collisions in which the dominant process is one of interactions between electronic clouds of the moving atoms. The energy at which a moving ion becomes a neutral one (an atom) can be estimated in the following way. Let the velocity of the moving atom be *v*. As an electron in the lattice will possess considerably lower velocity it can transfer to atomic electrons an amount of energy of no more than $m_e v^2$, and if the magnitude of this does not exceed the maximum ionization energy of the atom the latter remains neutral. Supposing the minimum ionization potential of the atom equals 2 eV we obtain that the energy E_n at which the atom becomes neutral is determined by the relation

$$E_n = \frac{1}{2}Mv^2 = \frac{1}{2}\frac{M}{m_e}I \cong \frac{1840}{2}A\,\text{eV} \tag{11}$$

In present circumstances it is the ion energy region $E < E_n$ which is of greatest interest since it is at just such energies that the majority of atomic displacements are generated. Such collisions occur when the kinetic energy of the moving atom is insufficient to allow its penetration through the atomic electron cloud. If the kinetic energy of the moving ion greater than E_n, then the resulting collisions can be considered as Rutherford scattering events, a situation in which atoms cannot be shifted from the lattice and the energy is therefore spent on producing lattice vibrations.

Point defect accumulation

The isolated defects, interstitial atoms and vacancies that are produced as a result of irradiation typically occur within close proximity to each other and therefore easily recombine, resulting in complete annihilation of the influence of the irradiation. Conversely, the point defects can also move away from each other and at sufficiently large distances interconnectivity will be lost. At rather high temperatures defects can

also begin to diffuse, 'walking over' the lattice so to speak. The fate of walking defects can be different. As an instance, they can meet polar defects and combine. In such a case complete annihilation (recombination) of the defect pair occurs. In polycrystalline solids the defect can also approach the grain boundary, and be absorbed if the total value of the surface energy decreases. Analogously, it is also possible for defect absorption on dislocations to occur (the latter always existing in a substance), or otherwise on impurity atoms. This process is often referred to as the heterogeneous origin of defect accumulation. A point defect diffusing through the solid can also meet another similar defect and form a coupled pair at rest. This pair can then play the role of an origin for condensation or other such defects of the same kind. Such a process is referred to as the homogeneous origin of defect accumulation. Finally, if the energy of the primary displaced atom is sufficient to form a displacement peak then the peak region can serve as a centre for accumulation.

2.3. Radiobiological Processes

Radiobiology is that branch of the biological sciences which studies the effects of ionizing radiations on living matter. Radiation biology found its origins in the more or less accidental observations of biological reactions that followed the very earliest exposures to ionizing radiation, being mostly those due to X-rays but also to the alpha, beta and gamma irradiations from radioactive sources. The first of these observations was made by Henri Becquerel who found a skin irritation after he had placed and carried a radioactive source in his pocket. The first directed radiobiological experiment was performed by Pierre Curie who repeated the Becquerel experience exposing the skin of his forearm to an alpha source and finding the same result.

At this time it was not possible to perform quantitative experiments on the effects of ionizing radiation, primarily because a quantitative biological detector system did not exist. Radiation was applied in an empirical way to cure tumors or in mutation research to produce genetic alterations in various types of cells.

Quantitative measurements of the biological action of radiation action became feasible when cultivation of bacteria and plant cells and finally of mammalian cells was finally accomplished. At around about the same time, the structure of DNA was understood and the famous double helix molecule was discovered to be the carrier of all genetic information. Almost simultaneously with this, it was found that the DNA in the cell nucleus was the primary target for attack of ionizing radiation. As a consequence of this a quantitative program of radiation biology research was initiated in the early 1960's.

The biological effects of ionizing radiation are caused by absorption of radiation energy in cells and tissues. If radiation passes through living material, without energy deposition, then no biological effect can be expected to result. However, if energy is deposited then the irradiation will produce ions, free radicals, excited atoms and molecules, and stable stricken structures; the primary physico-chemical effects become intensified with time due to the metabolic processes and leads to dependence on the magnitude of the dose, the type of radiation, the time of delivery of the dose (within the cell cycle), distortion of all biochemical and physiological processes in the cell and to the organism as a whole. Investigation of the mechanism of radiation influence on the

cell is one of the main problems of radiobiology, the question being one of trying to understand the nature of intracellular processes leading to the reinforcement of a radiation induced disease (radiocarcinogenesis) or in overcoming mutagenesis (the objective of radical radiotherapy). A live cell is a very complicated biological formation carrying within it the genetic information that determines the shape, metabolism and functions of the cell. A cell contains proteins, hydrocarbons, nucleic acids and other biopolymers. On the average, a cell contains up to 80% water, and its sum parts are a set of solutions of organic and inorganic compounds of different concentrations. As a result, in live cells two different types of damage may occur. The first is direct damage of the biologically dynamic molecules such as DNA molecules and cell membranes, i.e., depolymerization of biomolecules. The second type of damage is a consequence of indirect effects, resulting from the reaction of polymers with radicals formed from low-molecular substances, especially from water. The products of radiolysis of water ('lyse' has the meaning 'split apart') attack different biopolymer fragments, leading to their modification and thus to changes of their functional properties.

Different types of radiation differ in their effectiveness or efficiency in damaging a biological system, depending on the modality of energy transfer, i.e. the number and density of ionization events and excitations along the path of radiation. X- and gamma-rays are low ionization density radiations, while alpha particles, neutrons and heavy ions give rise to a high ionization density pattern.

The effects of ionizing radiation on living organisms can be classified in different ways, depending on the adopted criteria. A fundamental distinction is between stochastic and non-stochastic effects. The first type of effect are those, such as cell mutation, for which a correlation can be recognized between the dose of radiation and the probability that the effect occurs, rather than between the dose and the intensity of the effect. Conversely, non-stochastic effects are those for which a clear correlation between the dose (and/or dose-rate) and the intensity of the effect can be established. For these effects, such as cell inactivation, a threshold dose is recognized, below which no deterministic response can be observed.

From a biological point of view both stochastic and non-stochastic effects can be interpreted on a purely cellular basis; the former are, in general, the consequences of gene mutations or chromosomal aberrations while the latter arise from cell inactivation in organs or tissues. In either situation we are dealing with phenomena deriving from the same basic event: energy deposition in a living cell by an ionizing radiation event. This concept, well established during the 1950s, is of fundamental importance in the understanding of radiobiological phenomena in living organisms and on its basis the cell assumes the role of the leading character in the genesis of biological effects.

From a purely physical point of view, one major problem is the description of the physical events responsible for the damage to the biological target. For X-rays or gamma rays, ionization is produced by photo-, Compton- or pair effects or secondary electron collisions which occur in a probabilistic way. The spatial and time distributions of these events do not depend dramatically upon the maximum energy of the bremsstrahlung spectrum or the gamma transition energy. In order to investigate the influence of the primary processes of energy deposition, the use of radiation sources that

differed from that of the X-ray tube was found to be necessary. This became feasible with the advent of particle accelerators.

In a classical experiment carried out in 1968, G.W. Barendsen and co-workers used a range of cyclotron-produced heavy charged particles, including deuterons and helium ions, to measure the biological responses of cultured cells as a function of energy loss or linear energy transfer (LET) of the primary particle. For helium ions at an energy loss in water of around 100 keV μm^{-1}, a maximum value for biological efficiency was found, comparison being made with the response to equal doses of X-rays. This was interpreted to be the optimum ionization density necessary to produce simultaneous damage on the two opposing strands of DNA. Subsequently, for protons and carbon ions a shift in the value of the LET at which maximum efficiency occurred was found, the shift being to lower values of energy loss for protons and to higher LET values for carbon ions. The fact that the same dose of radiation can produce orders of magnitudes greater or smaller effects with change in radiation quality, i.e. the spatial distribution of primary events, is extremely important for the understanding of radiation action.

In radiation biology, theoretical understanding is confronted with an extremely difficult situation. On the one hand, the target for the ionizing radiation is an extremely large system comprising of an abundance of molecular types, each of them interacting with the others in thousands of well defined pathways in stark contrast with the statistical mechanical picture. On the other hand, exposure to sparsely ionizing radiation produces a vast chaos of ionized atoms and electrons, randomly distributed over the target volume. Theoretical understanding is to a large extent an abstraction from these two extreme and opposing situations, the only justification of any model being final agreement with the experimental data.

Swiftly moving heavy charged particles like protons, iron or even uranium ions, can only be produced in accelerators. While their impact on biological material is not an experience of our daily life, it is none the less true that the interaction of these particles with biological matter like DNA, cells or tissue is of extraordinary scientific and practical importance. In space research, highly energetic particles from protons to iron ions represent the most hazardous component of the cosmic radiation background. In space explorations, shielding is extremely costly, therefore experiments at heavy ion accelerators are required in order to explore the long term radiation risk for long-term space flights in an effort to ensure optimal shielding.

Over the last two decades a great range of charged particles and energies have been investigated in terms of their radiobiological consequence, from protons to uranium, and from a few MeV up to relativistic velocities respectively. From impressions, one might suggest that only the total energy deposition (the energy loss of the primary particle) is of importance in determining biological consequence. This would imply that two particles of different energies but giving rise to the same energy loss would cause the same biological effects. In part, investigations have borne this idea out: the results of extended experiments from many groups, using different biological system as targets, reveal a characteristic behavior for biological action of each particle as a function of the energy loss in the target material, this parameter being identical to the linear energy transfer. In Figure 4 this dependency is presented for the case of cell inactivation. For

extremely low energy transfers the action cross section is indeed proportional to energy deposition as suggested. However, for higher LET values, first a linear increase (in logarithmic scale) and then a saturation effect are observed, the value at which saturation occurs increasing with atomic number. The general pattern of the biological action cross-section is very similar for many biological reactions, including inactivation or induction of mutation and chromosome aberration and also for DNA damage like single or double strand breaks. In principle, for all particle energies and energy losses the physical reactions, ionization and electron emission, are the same. The difference is to be found in the probabilities of occurrence of these processes and the distribution of energy and angles of the emitted electrons. Therefore, the different biological response must be attributed to the different spatial and time pattern of these primary events.
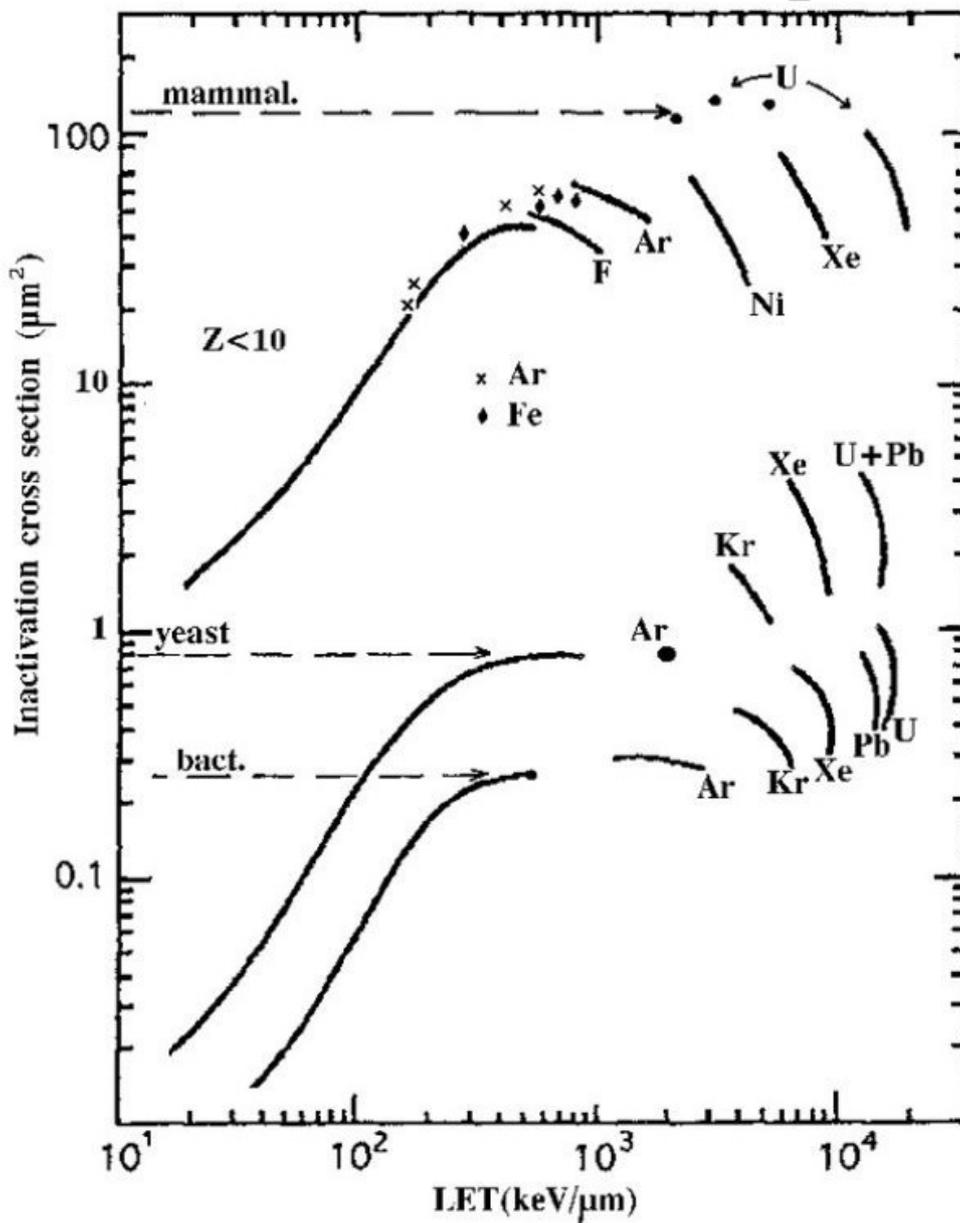

Figure 4. Action cross section for cell inactivation, i.e. the loss of colony forming ability as a function of linear energy transfer (LET). The experiments were performed with V-

79 Chinese hamster (mammalian) cells, yeast cells and bacteria spores.

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Biographical Sketches

David A.Bradley graduated Bachelor of Science (Physics) from the University of Essex in 1975. He has a Masters of Science (Radiation Physics) degree, awarded by the University of London in 1976, and a PhD awarded by the University of Science (Penang) in 1985. His career, which began with work as a radiotherapy physicist at Charing-Cross Hospital (London), has in more recent years, encompassed long periods of time in teaching and research at universities in Malaysia. Currently he is a senior lecturer and

member of the biomedical physics group at the School of Physics, University of Exeter. His research interests concern the general area of interactions and consequences of radiations in industry and medicine; a specific interest has been the elastic photon-atom scattering process. Journal publications number some 100 papers. In addition, he has been the editor of a number of books and special issues of journals which concern ionizing radiations. DAB is a fellow of three professional Institutes, the Institute of Physics (IOP), the Institute of Physics and Engineering in Medicine (IPEM) and the Malaysian Institute of Physics (IFM). He is an editor of the journal *Applied Radiation and Physics* and a Council Member of the International Radiation Physics Society (IRPS).

Tsipenyuk Yuri Mikhailovich, graduated from the Moscow Institute of Physics and Technology (MIPT) in 1962, becoming candidate of sciences in 1969, and doctor of physico-mathematical sciences in 1979. From 1961 until the present time he has worked at the P.L.Kapitza Institute for Physical Problems, Russian Academy of Sciences, now are being the leading scientist of this Institute. In addition he is Professor of physics of the Moscow Institute of Physics and Technology. His scientific interests include: electron accelerators, fission of atomic nuclei, activation analysis, investigation of the solid state by neutron scattering, and superconductivity. In 1997 he was made Soros professor and in 1997 he became a Member of the New York Academy of Sciences. Y.M.T. has published more than 120 papers in scientific journals, and is the author of three monographs: "Physics of Superconductivity" (in Russian, 1995, MIPT Publishing, Moscow), "Nuclear Methods in Science and Technology" (IOP Publishing, 1997), "The Microtron: Development and Applications" (Taylor & Francis, 2002), in addition to being the coauthor of a textbook on general physics for high school "Basics of Physics" (Nauka, Moscow, 2001).